SOIL STRUCTURE INTERACTION OF CORRUGATED BOX CULVERT

by

Nikhitha Johnson

Submitted in partial fulfilment of the requirements
for the degree of Master of Applied Science

at

Dalhousie University
Halifax, Nova Scotia
December 2023

Dalhousie University is located in Mi'kma'ki, the
ancestral and unceded territory of the Mi'kmaq.
We are all Treaty people.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Corrugated box culverts are essential components in the construction of infrastructure projects such as tunnels, bridges, and culverts. They have been popular in recent years as they are economical, maintain superior strength and have shorter construction periods. The soil-structure interaction of corrugated box culverts is influenced by several factors, including the soil properties, geometry of the culvert and loading conditions. However, several factors such as the backfill soil stiffness, the soil cover, and the trench geometry which affects the soil structure interaction of Corrugated Box Culverts (CBCs) for longer spans are not yet fully understood. Understanding and accurately modeling the soil-structure interaction is essential to ensure the safety and durability of the structure.

This paper aims to investigate the behaviour and performance of these innovative structures under different conditions by utilizing comprehensive numerical models. The case study selected for this research was the box culvert with different crown stiffness in Lidköping, Sweden. The finite element analysis results showed the culvert's crown displacements, thrust, and bending moment, making it possible to gain insight into the performance of such structures during backfilling. For numerical study, two-dimensional numerical models were developed using Plaxis 2D, which was verified against the field measurements. Furthermore, parametric studies were conducted to examine the crown displacement, thrust, and bending moment variations influenced by different model conditions. The study showed that the trench width and the trench side slope of the excavation were found to have only a negligible effect on the results. It was also found that varying the soil cover depth and stiffness of the backfill soil significantly affects the performance of the Corrugated Box Culvert.

LIST OF ABBREVIATIONS AND SYMBOLS USED

Abbreviations

2D	Two-dimensional
AASHTO	American Association of State Highway and Transportation Officials
BIS	Bureau of Indian Standards
CBC	Corrugated Box Culvert
CEN	European Committee for Standardization
CHBDC	Canadian Highway Bridge Design Code
FE	Finite Element
FEA	Finite Element Analysis
FEM	Finite Element Modeling
GUI	Graphical User Interface
HS	Hardening Soil
LRFD	Load & Resistance Factor Design
MLIT	Ministry of Land, Infrastructure, Transport & Tourism
MTO	Ministry of Transportation, Ontario
SSI	Soil Structure Interaction

Symbols

A	Cross-sectional area
B	Trench width
c’	Cohesion
D	Side angle
E	Elastic modulus
E_{50}^{ref}	Secant stiffness in standard drained triaxial test
E_{oed}^{ref}	Tangent stiffness for primary oedometer
E_{ur}^{ref}	Unloading/reloading stiffness

EA	Axial rigidity
EI	Bending rigidity
E_{st}	Elasticity modulus of steel
F_{yk}	Yield strength of the pile
I	Moment of inertia
m	Power of stress-level dependency of stiffness
R_c	Crown radius
R_h	Haunch radius
R_{int}	Interface strength reduction factor
S	Culvert span
t	plate thickness
t	Soil cover depth
γ	Unit weight
γ_{dry}	Dry unit weight
γ_{sat}	Saturated unit weight
ν	Poisson’s ratio
W	Section modulus
φ	Internal friction angle of the soil
Ψ	Dilatancy
Δ_c	Crown radius
Δ_h	Haunch radius

ACKNOWLEDGEMENTS

I begin with a prayer and thank THE ALMIGHTY for the immense energy bestowed upon me to proceed in the path of righteousness. I would like to thank God for giving me strength and courage throughout my research.

It is my proud privilege and honour to express my deep sense of gratitude to my respected guide Dr. Hany El Naggar, for his valuable guidance and for the constant support throughout. I am indeed fortunate to be studying under his supervision. I will always be indebted to him for his continuous support, patience, and encouragement during this research.

Finally, I take this opportunity to express my sincere gratitude and love to my family, friends, and colleagues for their huge amount of support and encouragement.

CHAPTER 1 INTRODUCTION

1.1 Research Background

Early in the twentieth century, when metal pipes were utilized to build modest drainage systems, corrugated box culverts made their debut. Pipes made of concrete were eventually installed in place of the older metal ones because of their greater resilience and lifespan. Corrugated steel plates were tried out by engineers in the 1950s as a cheaper and more effective alternative to concrete pipes for building box culverts. The use of corrugated steel plate culverts in the construction of bridges, tunnels, and storm water management systems has grown in popularity since then. Engineers began investigating alternative materials for making box culverts as the need arose for more long-lasting and effective infrastructure systems. Reinforced concrete was one such material since it was stronger and more long-lasting than regular concrete pipes. Precast reinforced concrete box culverts were first tested by engineers in the 1970s and quickly gained popularity due to their simple design, low price, and long lifespan. North America has a growing infrastructure deficit, where roads and highway systems are functionally and structurally deficient which needs to be replaced or rehabilitated. Replacement is the only acceptable option as the capital of rehabilitation becomes inhibitive and is technically impractical. Negligence of rehabilitation or replacement can lead to failure and causes economic and environmental disruption. An economic and effective alternative to conventional bridge design is required to optimize tax dollars.

Corrugated box culverts are an important aspect of civil infrastructure, widely used in the construction of roadways, bridges, and railways. They have been used as an effective alternative to short-span bridges because of their reliability, durability, lightweight, and ease of installation and can meet the design and safety requirements for traditional bridges, at lower initial and long-term maintenance cost. It has a deep corrugated structural plate, the ridges; and grooves on the surface of the metal, provides stiffness to the culvert, as a result increases the structural strength of the culvert. Corrugated box culverts can easily be constructed as the structure is assembled in the field using several corrugated structural plates, with bolts and nuts. This installation process is easy and efficient, hence making them preferable for construction projects. Another remarkable advantage is their durability and being environmentally friendly. They are resistant to corrosion and can withstand heavy rainfall and floods. As a result, corrugated box culverts are an ideal solution for many construction projects that require lifelong low-maintenance structures. Figure 1.1 shows an example of corrugated box culverts that have become more common over the last 20-30 years for use under highways, railways etc.

Figure 1.1. An example of a Corrugated Box Culvert used for highways and railways (Atlantic Industries Limited)

Due to the advancements in computer technology, finite element models have become increasingly complex enabling engineers to predict the behaviour of culverts more accurately under a variety of soil conditions. Because of this, design guidelines and standards for corrugated box culverts were eventually developed that incorporated consideration of the interaction between the soil and the structure. In modern times, the design of corrugated box culverts often entails a thorough investigation of the soil conditions present at the site, in addition to an examination of the function that the culvert is supposed to serve.

Using finite element analysis (FEA), the Plaxis 2D software can generate numerical models of corrugated box culverts for the purpose of investigating their soil-structure interaction. Eventually, after applying both the dead load and the truck load, the stresses and deformations caused by both loads are studied in this model. The culvert is subjected to a constant dead load that represents the combined weight of the culvert and any additional materials placed on top of it. Additionally, the software also provides the option to replicate the truck load, either by applying the load all at once or spreading it out evenly across the ground. Because of this, the forces that the structure will experience over its lifetime may be more accurately modelled.

One of the primary challenges in designing corrugated box culverts is accurately predicting the SSI. Accurately modelling this interaction requires a deep understanding of the underlying mechanics and the ability to model it correctly. Several analytical and numerical methods are available to model the SSI, each with its own advantages and limitations. The most used methods include finite element analysis, boundary element analysis and analytical methods like the Winkler model. Accurate modelling of the SSI is crucial in designing corrugated box culverts. Improper design can lead to several problems, including excessive deformation, cracking or even culvert collapse. Additionally, incorrect predictions of the SSI can result in overdesign, leading to higher costs and unnecessary use of resources. Therefore, it is essential to conduct a thorough analysis of the SSI during the design process to ensure the optimal performance of the structure. Additionally, several environmental factors affect the SSI of corrugated box culverts, such as temperature changes, moisture content and seismic activity. Temperature changes can cause the culvert to expand or contract, leading to changes in the interaction with the soil. Moisture content can affect the stiffness and strength of the soil, impacting SSI.

The connection of the soil and the structure is a significant concern during the construction and installation of corrugated box culverts, in addition to the design process. To ensure that the culvert will be adequately supported, the soil must be well compacted, and proper backfilling procedures must be followed in order to prevent settling and movement of the soil surrounding the culvert. SSI of corrugated box culverts is a complicated phenomenon that depends on a variety of variables, such as the shape of the culvert, the loading circumstances, and the surrounding environment (Ezzeldin, & El Naggar, 2021). The choice of approach for modelling the SSI can be made using a variety of analytical and numerical techniques, depending on the needs of the individual project.

The need for precise modelling of the SSI for longer spans is growing as authorities are demanding better and safer options. However, most of the studies have focused only on the short-term performance under backfilling and static loads. Currently, there is not an adequate amount of published data available on the structural behaviour of the metal culverts on a long-term basis. Hence, this research aims to investigate and improve the performance of corrugated box culverts, by using finite element modelling (FEM) with PLAXIS 2D for different culvert profile cases. Advanced two-dimensional FE models using the PLAXIS software are developed to mimic the deformation of the structure, where the corresponding axial force and bending moments are verified against available field measured data in Lidköping, Sweden. In addition, comprehensive parametric studies were conducted to investigate the deformations, the bending moments, and the axial forces in response to varying the culvert profile, culvert dimensions, soil cover depth, and backfill soil.

1.2. Research Objectives

This research aims to numerically analyze the performance of deep corrugated box culverts during the backfilling and static conditions. For this thesis, the primary objectives of the conducted research can be stated as follows:

- Investigate the field measured corrugated box culvert during backfilling stages in Lidköping, Sweden.
- Develop comprehensive two-dimensional finite element models using the full continuum approach to study the performance of the corrugated box culvert and verify the deformation, bending moment and thrust against the field acquired data.
- Conduct parametric studies using the calibrated models to investigate the changes in the deformation, bending moment, and thrust under various conditions.

1.3. Thesis outline

The chapters contained in this thesis are ordered as follows:

- **Chapter 1** Introduces the research topic for this thesis and the corresponding objectives.

- **Chapter 2** Literature review presents extensive details related to the CBC construction and design concepts. In addition, current design practices and guidelines employed across various regions worldwide are discussed in this chapter.
- **Chapter 3** Development of a comprehensive 2D non-linear finite element model that can stimulate the structural response of the Corrugated Box Culvert during backfilling stages. The model is calibrated by comparing its numerical results with the field-acquired data.
- **Chapter 4** Two-dimensional modelling of a corrugated box culvert and presents the results of the conducted analyses for different culvert profile cases.
- **Chapter 5** summarizes the key findings, conclusions, and recommendations for this thesis.

CHAPTER 2 LITERATURE REVIEW

2.1. Full Scale tests

Corrugated box culverts have become popular in recent decades as they were designed with the purpose of fulfilling the requirement for a structure that can offer a wide space despite limited height clearance. They are an effective and economical alternative to short-span bridges because of their durability, reliability, lightweight, and construction. Also, they can meet the design and safety requirements for traditional bridges with low initial and long-term maintenance costs. The structural strength of the culvert is more as it has a deep corrugated structural plate, which provides stiffness to the culvert. Hence, it helps to prevent excessive deflections from occurring during backfill and to improve buckling resistance. The performance of buried corrugated box culverts is influenced by the characteristics of both the structure itself and the surrounding soil, leading to interactions between the two. As a result, most studies investigating the structural mechanics of corrugated box culverts involve observing the actual behaviour of the buried structure. This observed behaviour is then compared to calculations obtained through finite element analyses (Moore and Brachman, 1994; Webb et al, 1998; Moore and Taleb, 1999; Kim and Chai,2005; Kunecki, 2006; Kitane and McGrath, 2006; Bayoglu Flener, 2009).

Due to the relatively recent introduction of Corrugated Box Culverts, their complex response to backfilling and associated soil-structure interactions (SSI)s has yet to be completely understood. Nevertheless, through the utilization of finite element methods (FEM), scientists can carry out numerical investigations to examine how performance is affected by different circumstances. In order to comprehend the intricate soil structure interactions (SSIs), related to Corrugated Box Culverts (CBCs) during backfilling, researchers have conducted extensive monitoring and numerical analysis to explore laterally under various site conditions. As an illustration, Byrne (1978) conducted a comprehensive examination of a rib-reinforced metal box culvert with a considerable span in order to investigate the structural response of such systems throughout the building phase and under dynamic loads. The culvert exhibited a span measuring 4.8 meters and a rise measuring 1.5 meters. The formation of the structure involved the utilization of corrugated structural plates measuring 152 mm by 51 mm, which were further reinforced with corrugated ribs at both the crown and shoulder sections. The author's conclusion suggests that the incorporation of ribs in these constructions effectively reduces the occurrence of peaking deflections when subjected to backfilling. Additionally, it was observed that there is a greater uniformity in the distribution of thrust force as the depth of soil cover increases.

McCavour et al. (1998) conducted comprehensive experiments on two long-span deep-corrugated reinforced steel box culverts, each subjected to varying backfill densities. The experiments assessed the utilization of encased concrete composite ribs in comparison to traditional continuous reinforcing. The two structures exhibited a span of 12 meters and a rise of 3.1 meters. The performance of both culverts was observed throughout the process of backfilling and under the influence of live load. The researchers discovered that a minimum cover of 0.30 m is appropriate for the design and implementation of long-span box culverts with these specific types of stiffeners. Additionally, it was determined by the researchers that the deformation of the structure is greatly influenced by the density of the backfill. This behaviour is widely recognized in the context of typical corrugated plate constructions. The deformations observed in the structure filled with loose soil were found to be three times greater than those observed in the structure filled with dense soil.

Additionally, the bending moments experienced by the structure filled with loose soil were determined to be 50% higher compared to the structure filled with dense soil.

In the study, Manko and Beben (2005) provided a comprehensive overview of the tests conducted on a long-span deep-corrugated reinforced steel metal culvert. The culvert exhibited a span measuring 12.3 meters and a rise measuring 3.55 meters. To enhance the structural integrity, supplementary layers of corrugated plate and ribs were strategically positioned, extending from the uppermost point to the lower sections, encompassing both the shoulders and side walls. Following the completion of the installation process, the structure underwent backfilling with soil that was carefully put in layers and compacted to achieve a density of 95% of the maximum dry unit weight determined using a standard Proctor test. The authors reached the conclusion that achieving full interaction between the structure and the surrounding soil is contingent upon the right laying and skillful compaction of the soil until the desired amount of compaction is attained. From the analysis of the strain measurement, it was observed that the structural response to the earth load exhibited predominantly elastic behaviour. Furthermore, the deformations experienced throughout the backfilling process were discovered to be far lower than initially anticipated. The magnitude of the structural deformations subsequent to backfilling was found to be comparatively reduced in relation to the values obtained from two-dimensional finite element analysis.

The study conducted by Morrison (2005) detailed the process of installing and conducting tests on a deep-corrugated steel box culvert with encased concrete ribs, spanning a distance of 14.1 meters. The structural behaviour was observed and recorded during the processes of backfilling and testing with a truck. The Ministry of Transportation, Ontario (MTO) put instrumentation on the structure and performed live load tests as part of its research and development endeavours. Based on the examination of the test outcomes, Morrison reached the conclusion that metal box culverts with encased concrete composite ribs of considerable length have the capacity to effectively withstand the stress imposed by highway traffic, particularly when spanning distances of up to 14 meters. The study conducted by the author revealed that the utilization of the CHBDC vehicle loading, load factors, and load distribution provisions in the design of the test structure was characterized by a cautious approach. It was suggested that doing a parametric investigation on long-span deep corrugated box culverts, encompassing diverse geometries, covers, live load intensity, and live load placements, would be necessary in order to derive simplified equations applicable to the design process.

In a controlled laboratory setting, Lougheed (2008) conducted comprehensive tests on a deep-corrugated box culvert with a 2.4 m rise and a 10.0 m span that was buried below. A total of twenty-one tests were carried out to investigate the behavior of the structure under various conditions. These conditions included evaluating the response of the structure without backfill, during the backfilling process, under the load of a tandem axle dump truck, and under simulated vehicle loading using an actuator. Two experiments were carried out with forces beyond the specified design values in order to determine the ultimate limit state(s) of the construction. During the initial test, a critical threshold was reached at around 800 kN, indicating the occurrence of an ultimate limit condition. This state was observed when the geotechnical resistance beneath the loading pads was surpassed. In the subsequent test, larger loading pads were employed, hence enabling the application of greater magnitudes of force. The structure reached an ultimate limit condition when three plastic hinges formed under a combined surface stress of 1100 kN. The plastic hinge is first created at the crown, and then, hinges are formed at each shoulder.

In a study conducted by Flener (2010), a set of comprehensive field tests were performed on four long-span deep-corrugated steel box culverts. These culverts had spans measuring 14 and 8 meters. The culverts were initially subjected to service load levels, followed by the application of larger loads. According to Flener (2010), the culverts were subjected to ultimate loads. Nevertheless, the imposed loads failed to induce the culvert to reach its ultimate condition, characterized by the production of plastic hinges at the crown and shoulder. The calculated maximum bending moment was around 80% of the moment capacity of the box culvert in the absence of any crown ribs. The author's conclusion is that the live load moment equation proposed by the Canadian Highway Bridge Design Code (CHBDC) is deemed acceptable for box culverts that have spans of less than 8 meters. Additionally, the author observed a significant increase in the final load carrying capacity when crown stiffeners were employed. The accurate prediction of the increase in flexural rigidity of the stiffened components proved to be challenging. The strain levels observed at the crown level suggest that the load-bearing capacity of the structures is increased twofold by the implementation of stiffening measures at a depth of 45 cm. The stiffening effect diminishes as the depth increases.

2.2. Finite Element Analysis

Over the past two decades, there has been a continuous improvement in the capability of finite element analysis to effectively simulate and evaluate soil structure interaction issues related to long span culverts. The majority of the research conducted during this time period has predominantly focused on two-dimensional analysis. Several recent research have utilized three-dimensional analysis techniques in the examination of long span metal culverts. The subsequent section provides an overview of the research conducted utilizing finite element analysis to investigate the structural characteristics of extended metal culverts.

In the study, Seed and Raines (1987) conducted a modelling analysis to examine the collapse of a metal culvert with a lengthy span during the construction phase, specifically in the presence of an extraordinary live load. The failure of the culvert occurred subsequent to the passage of a substantial dump truck transporting backfill in close proximity to the structure, resulting in the deposition of its material in areas where the culvert had not been adequately buried up to its highest point. Two plastic hinges were observed to have formed; nonetheless, it is noteworthy that this occurrence did not result in a complete collapse of the culvert. In order to simulate structural failure in the given circumstances, Seed and Raines conducted a two-dimensional study employing an elastic soil material and a nonlinear elastic model for the culvert material. The equation formulated by Duncan and Drawsky (1983) was employed to determine a line load that is equivalent to the truck loading. This determination was made by incorporating a modification that takes into account the equivalent cover depth. The analysis did not take into account the three-dimensional effects of the vehicle, the plasticity of the soil and culvert material, and the physical corrugation of the plates.

Girges and Abdel-Sayed (1995) conducted finite element analyses using the ABAQUS software (Hibitt et al., 1989) to investigate the structural response of long span metal culverts. The analysis made the assumption of an ideal relationship between the culvert and the soil. Two soil models were employed in this study, namely the elastic model and the extended elastic-plastic Drucker-Prager model. The purpose of the research was to get insight into the behavior of long span metal culverts under live loads. However, the analysis did not take into account the behavior of the structure during backfilling. The analysis focused exclusively on plates exhibiting shallow corrugation, while neglecting to incorporate the physical representation of the corrugation in the plate models. Based on the authors' comparative analysis of the outcomes derived from two-dimensional and three-dimensional analyses, it was determined that the utilization of three-dimensional modeling techniques results in a substantial decrease in bending moments.

Taleb and Moore (1999) conducted analyses in both two and three dimensions in order to simulate the response of long span shallow-corrugated metal culverts under the conditions of backfilling and live loads. The study utilized a semi-analytical approach in the three-dimensional analysis. This approach involved the implementation of a two-dimensional finite element mesh and Fourier integrals to accurately assess the load variation and response of the culvert in the axial direction. The authors of the study conducted a modeling analysis to examine the relationship between soil modulus and stress level. They also introduced a novel model for soil compaction, which establishes an upper limit for structural behavior. It is important to note that the suggested model does not account for plastic strains resulting from soil compaction. The findings of this analysis serve as the foundation for the prevailing design methodology outlined in the American Association of State Highway and Transportation Officials (AASHTO) design code. The finite element studies were conducted, and the findings were compared to the field tests conducted by Web et al. (1998). The analyses conducted in this study involved the utilization of an elastic structural model, despite the fact that the obtained results were subsequently employed in the development of a limit states design approach for long span metal culverts. The explicit representation of the physical corrugation of the structural plates was not included in the study, as orthotropic shell theory was utilized. Additionally, the analysis only accounted for shallow corrugated plates.

Morrison (2000) conducted a two-dimensional analysis on a long span deep-corrugated metal culvert with encased-concrete composite ribs, utilizing a finite element analysis program specifically developed for the analysis of such structures. The soil material was modeled using a nonlinear elastic model that incorporates a modulus that is dependent on the mean stress level. The structure that was strengthened was represented using beam elements in the model. The structure was assumed to possess elastic properties, while also accounting for the geometric nonlinearity of the beam parts. The consideration of soil compaction was omitted.

In 2002, Mohammed et al. conducted a two-dimensional finite element analysis on a shallow-corrugated metal culvert with transverse stiffeners and concrete thrust beams (longitudinal stiffeners) that spanned a considerable distance. The finite element software tool known as CANDE was utilized. The hyperbolic soil model proposed by Duncan et al. (1980) was employed to simulate the behaviour of the soil. The structure was characterized by a linear elastic material model. The analysis assumed a complete connection between the two surfaces. Instead of incorporating a detailed representation of the transverse stiffeners affixed to the structure, the attachment points of the stiffeners were simulated as roller supports in the model. The compaction of the layer was modelled by assigning an equivalent vertical pressure at the time of its placement, as done by the authors. The applied vertical pressure was twice the magnitude of the static pressure generated by a D-4 Caterpillar dozer.

In a study conducted by Moore and Brachman (1994), the Deux Rivieres culvert was modeled. El-Sawy (2003) subsequently performed a three-dimensional finite element analysis on this culvert. The three-dimensional analysis conducted by Moore and Brachman utilized a semi-analytical technique that relied on a two-dimensional finite element mesh positioned in the vertical plane, which was perpendicular to the axis. Additionally, Fourier integrals were employed to account for load fluctuation and culvert response in the axial direction. El-Sawy conducted a comprehensive three-dimensional analysis in order to examine the performance of the identical structure under dynamic loads. The structure was designed based on orthotropic shell theory, which did not explicitly account for the physical corrugation of the structure. In the analysis, it was assumed that both the soil and the culvert materials exhibited elastic behaviour. Subsequently, a comparison was made between the obtained results and the measured values, as well as the findings reported by Moore and Brachman (1994). The research was conducted utilizing an elastic model to represent structural behaviour. The study exhibited an overestimation of the measured thrusts, with an approximate discrepancy of 33%.

In 2004, Choi et al. conducted a two-dimensional finite element analysis on metal culverts with long spans ranging from 6 to 20 m. The analyses were conducted with the finite element software CANDE-89 (Musser, 1989). The authors endeavoured to assess the moment equation as outlined in the 2000 Canadian Highway Bridge Design Code (CHBDC) for metal box culverts. The analysis incorporated both shallow and deep corrugated structural plates. The construction was conceptualized as a collection of linear elastic beam elements. The hyperbolic stress-strain relationships proposed by Duncan et al. (1980) were utilized to model the soil. The researchers reached the conclusion that two equations representing the bending moments have been put forth for spans ranging from 6 to 11 meters and spans ranging from 11 to 20 meters. The author also deduced that the moment equation specified in the 2000 Canadian Highway Bridge Design Code (CHBDC) is conservative; and then presented additional equations for implementation. Nevertheless, their estimations were determined to be excessively cautious. The predicted bending moments for some scenarios exceeded the moment capability of the deep-corrugated sections.

In the study, Machelski and Antoniszyn (2004) conducted a three-dimensional finite element analysis on a long span metal culvert, employing two distinct methodologies. The initial approach involved conceptualizing the structure as an orthotropic shell, with the determination of its parameters relying on the equilibrium condition of the stiffness of a physically corrugated plate. The second solution employed a grid-like configuration of beams, encompassing both circumferential and transverse beams with distinct flexural and axial stiffness properties. The building and the soil were both represented as elastic materials. The relationship between the structure and the soil was simulated using spring elements that possess linear elastic properties. The researchers reached the conclusion that employing a grid-like arrangement of beams to represent the structure effectively anticipated the deformations. However, notable disparities were seen between the outcomes of the internal forces and the corresponding measurements obtained on-site. The authors encountered challenges when it came to presenting the findings related to shell elements.

In a laboratory setting, Kunecki (2006) conducted a finite element analysis on a shallow corrugated long span metal culvert, employing a three-dimensional approach. The analysis was conducted with the finite element software COSMOS/M. The researcher examined the behaviour of the structure under various static loading circumstances. The soil was simulated utilizing an elastic-plastic model, whilst the structure was considered to exhibit elastic behaviour throughout the research. The structure was designed based on orthotropic shell theory, wherein the equivalent thickness was determined as the depth of corrugation. Additionally, the modulus of elasticity was adjusted to get the desired EI value. The author had difficulties in accurately representing the boundary conditions of the full-scale test in their model. Due to the aforementioned issue, the finite element analysis failed to accurately determine the displacements and forces within the culvert.

2.3. Soil Structure Interaction

The soil structure interaction of culverts plays a critical role in determining the stability and longevity of the structure. Studies on soil structure interaction have been analyzed using various methods such as finite element analysis and empirical design equations. To determine their load carrying capacity, Waqas et al. (2023) carried out an experimental investigation on reinforced concrete box culverts with different haunch shapes and extra steel reinforcement. In order to assess the effects of haunch shape and additional steel reinforcement on the strength and stiffness of box culverts, the authors combined analytical and experimental methodologies. Based on the findings, it was possible to increase the haunch's thickness, add more steel reinforcement, and use the haunch's ideal shape to increase the load carrying capacity of box culverts. The results of this study have important ramifications for the development of reinforced concrete box culverts. In order to increase the load carrying capacity of box culverts, which is essential for guaranteeing the security and resilience of infrastructure, additional steel reinforcement and haunch shape can be used. The work can serve as a foundation for additional research in this field and offers useful insight into how reinforced concrete box culverts behave under various stress circumstances.

A numerical study on the performance of large-span arched soil-steel structures under soil loading was done by Embaby et al. (2022). The authors used finite element analysis to assess how soil-steel constructions behaved under various loading circumstances. The impact of soil-steel interaction on the structural response of large-span arched structures was the main topic of the study. The findings show that the soil-steel interaction greatly influences the structural behaviour of large-span arched structures, and failure mechanisms vary depending on the level of soil-steel contact. The design and construction of large-span arching soil-steel structures depend heavily on the study's conclusions. The study emphasizes how crucial it is to consider soil-steel interaction during the design phase in order to guarantee the structural integrity and safety of large-span arched constructions. The study offers important information on how soil-steel structures behave under various loading scenarios, which might serve as a foundation for future studies in this field.

To investigate the effect of vertical earth pressure on box culverts, Chu et al. (2022), used a centrifuge model for their experiment. The authors conducted several centrifuge tests in order to investigate the influences that type of soil, soil density, and backfill depth have on the amount of vertical earth pressure that box culverts experience. According to the findings of the research, the vertical earth pressure that acts on culverts increases with both the soil density and the backfill depth. According to the findings, the type of soil influences the amount of vertical earth pressure that is exerted on box culverts. The results demonstrated that cohesive soils have a higher level of vertical earth pressure than non-cohesive soils do. The findings of this research have important repercussions on the way box culverts are planned and built. According to the findings of the study, it is critical to ensure the structural soundness and safety of box culverts during the design phase to consider the characteristics of the soil as well as the depth of the backfill. This research also provides valuable insights into the actions of culverts under various loading conditions, which may serve as a ground for further study in this field.

Fu et al. (2023), put a medium-sized double-span box-type corrugated steel bridge through a field test in order to examine the structural performance of the bridge under a variety of various loading circumstances. The scientists monitored the structural response of the bridge by using strain gauges and displacement sensors to determine how the bridge reacted to varied loading conditions. According to the findings of the investigation, the bridge has good structural performance under both dynamic and static loading conditions. The researchers could not find any evidence of major damage or deformation. The results of this study are crucial for the planning and building of box-type corrugated metal bridges. This research sheds light on the structural performance of these bridges when subjected to a variety of loading circumstances, which is an extremely important aspect of guaranteeing their safety and longevity. The study offers useful insights into the behaviour of carton corrugated steel bridges, that can serve as a foundation for further research in this field.

Ezzeldin and El Naggar (2021) performed a three-dimensional finite element modeling to analyze the behaviour of corrugated metal pipes under various loading scenarios. The authors assessed the effect of the pipe diameter, the corrugation profile, and the soil characteristics on the structural response of corrugated metal pipes using numerical simulations. According to the study, the structural behaviour of corrugated metal pipes is highly impacted by both soil characteristics and pipe width. The outcomes additionally demonstrated that the corrugation profile affects how well the pipes operate structurally, with deep corrugations outperforming shallow corrugations. This study's conclusions have a big impact on how corrugated metal pipes are designed and built. The study emphasizes how vital it is to take soil characteristics and pipe diameter into account during the design phase in order to guarantee the structural integrity and safety of corrugated metal pipes. The study offers useful information about how corrugated metal pipes behave under various loading scenarios, which might serve as a foundation for future studies in this field.

Hakro et al. (2022) states that geotechnical engineers and academics can use Plaxis 2D to examine the behavior of a corrugated box culvert, a type of underground drainage system. Alternatively, engineers are able to forecast how a structure will respond to a variety of loads by simulating the system in 2 dimensions. In addition to powerful modelling capabilities, the software also features a graphical user interface (GUI) that provides the engineer with real-time visualization of the results. In order to examine the behaviour of a corrugated box culvert in Plaxis 2D, the soil-structure system's material attributes and boundary conditions must first be defined. Soil type, culvert pipe characteristics, and loading conditions must all be specified. Soil and structure stresses, strains, and deformations are then computed by the program using the finite element method.

Analysis of a corrugated box culvert can be used to determine the stability of the structure, optimize the design of the culvert, and assess the effects of different loading conditions on the system. Plaxis 2D can also be used to calculate the bearing capacity of the soil and the settlement of the structure, as well as the magnitude and direction of water flow around the culvert. Static and dynamic analysis, staged building, soil-structure interaction, and consolidation analysis are just a few of the analysis tools that Plaxis 2D has to offer. The software can also be used to analyze the effects of flooding on the stability of the culvert and the surrounding soil, as well as the effects of thermal expansion and shrinkage on the structure. The outcomes of a Plaxis 2D study can be used to determine the suitability of a corrugated box culvert for different applications, such as storm water drainage or agricultural irrigation. By providing advanced modelling capabilities and a user-friendly interface, Plaxis 2D is an invaluable tool for geotechnical engineers and academics who need to analyze the behaviour of a corrugated box culvert.

Generally, the sources reviewed in this literature review provide valuable insights into the behaviour of different types of infrastructure under soil loading. The studies highlight the importance of considering soil properties, loading conditions and design parameters in the design and construction process to ensure the structural integrity and safety of infrastructure. The findings of these studies can be used as a basis for further research in this area and can inform the development of design guidelines and standards for different types of infrastructure.

2.4. Advantages and disadvantages of Corrugated Box Culvert

Corrugated box culverts have recently become widespread in civil infrastructure because of their structural strength and durability. They have low initial and maintenance costs and can easily be installed. They can withstand heavy traffic loads and are highly resistant to corrosion, rust, and other environmental factors as they are made of galvanized steel or aluminum. However, exposure to harsh environmental conditions and heavy traffic loads can lead to degradation and the need for replacement. They can be susceptible to deformation or bending due to heavy traffic loads, ground settlement, and improper installation which further affects their functionality and performance. Hence, this section highlights attributes and limitations of using corrugated box culverts.

2.4.1. Attributes

Corrugated Box Culvert construction has been associated with lower construction costs as they require less material and labour for construction, leading to potential cost savings. Their prefabricated nature, ease of installation, and lower material costs contribute to overall cost savings. This is supported by a study conducted by Elhaddad et al. (2019), where researchers discuss the cost-effectiveness of using corrugated box culverts in various applications. Despite their lower stiffness compared to rigid structures, corrugated box culverts still exhibit sufficient structural integrity and can withstand normal traffic loads and environmental forces. (Hussein H, Ali H., Shia S. I., & Hamid M. T., 2018). The corrugated design enhances their structural integrity by effectively distributing loads which further leads to improved load-bearing capacity and resistance to soil and hydrostatic pressures. A case study by Paryavi et al. (2020) highlights the effectiveness of corrugated box culverts in withstanding high external pressures. Corrugated box culverts offer versality in design and can be customized to fit various project requirements. The prefabricated nature of CBCs simplifies the installation process, leading to reduced construction time and costs. In an article published by Jia et al. (2020), the authors discuss how the use of prefabricated box culverts can significantly reduce on-site construction time and minimize traffic disruption. They can be quickly assembled and installed, resulting in time savings during construction. Finally, CBCs exhibit excellent structural integrity and resistance to heavy loads (Anwar et al. 2017).

2.4.2. Limitations

Given the many attributes associated with CBCs, researchers have also indicated their limitations. CBCs have several limitations that affect their durability, performance, and resistance to environmental factors. Corrugated Box Culverts have limited structural strength and can fall under high load or dynamic forces. Due to insufficient wall thickness or inadequate backfilling, CBCs are susceptible to buckling, flattening, and collapse. A study by Abdel0Mooty and Seleem (2019) revealed that the bearing capacity of corrugated steel culverts decreases with increasing diameter and thickness. CBCs require proper installation and maintenance to ensure long life and functionality. The installation process involves careful backfilling, compaction, and adequate support to prevent deformation, settlement, or misalignment. Maintenance activities such as cleaning, debris removal, and repairs may also be necessary to prevent blockage, flooding, or erosion. Plancher et al. (2017) emphasizes the importance of proper installation practices and recommends the use of geosynthetics for erosion control and reinforcement. Corrugated culverts made of steel or aluminum are prone to corrosion, which causes rusting, pitting, and perforation. The corrosion process can be accelerated in acidic or saline soils and corrosive environments. According to Wang et al. (2016) the corrosion rate of corrugated steel culverts increases with time and depends on several factors such as pH, moisture content, and oxygen availability. Corrugated box culverts have limited span lengths compared to other steel culverts. This limitation is due to the fact that corrugated box culverts rely heavily on the strength of their walls and the rigidity of the structure. This can restrict their use in larger projects and in areas with high traffic volumes.

2.5. Loads on CBCs

Culverts have been constructed under highways, airport pavements, and railway tracts. Loads subjected on corrugated box culverts (CBCs) are categorized into two general types: dead load and live load. The amount of dead and live loads acting on the culvert depends on the height of the embankment above the culvert, the material used for the backfill, and the degree of compaction of the backfill.

2.5.1. Dead loads

Generally, the dead loads on the culvert include self-weight of the structure, compacted backfill, and any additional permanent loads such as utilities or pavement layers above the culvert. These loads account for the permanent weight that the culvert needs to bear throughout its service life. The dead loads on CBCs may vary depending on the culvert's dimensions, material, bedding, and backfill material used. Dead loads account for a significant portion of the total design load on culverts and are essential in their structural design.

2.5.2. Live loads

The live loads on the box culvert are typically the result of loads and forces that act upon the culvert due to vehicular or pedestrian traffic plus an impact factor. They are often used in transportation infrastructure and are designed to carry various types of traffic loads, including heavy trucks and vehicles. Overall, the design and load-carrying capacity of corrugated box culverts depend on various factors, such as material properties, size, and shape, as well as the loads applied.

2.6. Design and Analysis of Corrugated Box Culvert

Corrugated box culverts are an essential and adaptable component of civil engineering infrastructure that serve a variety of significant purposes in modern society. These ducts are basically empty, roundabout, or rectangular developments that are habitually worked of supported concrete or ridged metal. They are expected to convey water, oblige streets or trains, and proposition safe entry for natural life and people. Box culverts have been around for a long time. The first ones were masonry structures that did the same thing (Duncan et al., 2015). However, the need for cost-effective and simple-to-install solutions for the expanding drainage and transportation networks prompted the development of corrugated box culverts into what they are today in the middle of the 20th century. These culverts' walls consist of ridges or corrugations that greatly improve their structural stability while using less material. This invention transformed the building sector by enabling effective and affordable solutions for a variety of uses. Corrugated box culverts are a staple of civil engineering projects all over the world due to their longevity and ability to adapt to a variety of geographic and climatic circumstances. These culverts are not just passageways; they are essential lifelines that guarantee the efficient and secure movement of people, products, and water. The sustainable growth and upkeep of crucial infrastructure systems in the current period depends on an understanding of their history and technical principles. Therefore, this section will provide an in-depth exploration of the design and analysis of corrugated box culverts, shedding light on the engineering principles, structural considerations, and global design practices.

2.6.1. Structural Elements and Design Principles of Corrugated Box Culverts

Corrugated box culverts are essential civil engineering components created to improve infrastructure resiliency, promote water flow, and enable passage for multiple types of transportation. In-depth examination of the structural components and design ideas supporting the operation and durability of corrugated box culverts are:

A. Components of Corrugated Box Culverts

- **Crown**:

The crown, an essential part of corrugated box culverts, acts as the uppermost structure to support the weight of external loads like dirt and vehicles. In order to guarantee the structural integrity and lifespan of the culvert system, it's design and capacity are crucial. The main purpose of the crown is to distribute external loads uniformly throughout the whole culvert structure. To avoid localized stress concentrations that could cause deformation or failure, the loads must be distributed evenly (Sargand et al., 2018). The crown ensures that the culvert is stable and keeps its shape when traffic goes over it by distributing the load from the side walls to the base and finally to the side walls.

The type and weight of vehicles that will cross the culvert must be carefully taken into account when designing the crown. Calculations based on variables like traffic volume and axle weights for vehicles are essential for figuring out the size and load-bearing capacity of the crown. The design of the crown must guarantee that it can securely sustain this weight without undergoing too much stress or deformation.

- **Inverts**:

Inverts occupy the bottom portion of the structure, creating the channel through which water or other fluids flow. Their construction is crucial to enabling effective hydraulic conveyance, cutting down on turbulence, and limiting debris buildup. The inverts' shape and slope significantly impact how well a culvert performs hydraulically (Tawfiq, 2012). A key goal in culvert design is effective hydraulic transport. To provide a smooth flow path and reduce energy loss and turbulence inside the culvert, inverts should be carefully built. Turbulence can cause erosion and sediment buildup, which can reduce the culvert's capacity and lifespan. Therefore, turbulence must be reduced.

The hydraulic performance of the culvert is substantially influenced by the shape and slope of the inverts. Engineers can alter these variables to regulate flow volume and speed. A broader and flatter invert can accept greater volumes of water at lower velocities, whereas a steeper slope can enhance flow velocity. Hydraulic calculations based on flow rates, anticipated water levels, and desired velocities are crucial for optimizing inversion design (Frankiewicz et al., 2021). Decisions about inverted dimensions, such as width, height, and slope, are influenced by these calculations (Karimpour & Gohari, 2020). The design is further improved by hydraulic modeling and simulations to guarantee that the culvert achieves its hydraulic efficiency objectives. Therefore, effective inverts are essential to lowering the costs of culvert system maintenance as well as flooding, erosion, and flooding. They are a crucial component of a better corrugated box culvert design because their appropriate design and alignment inside the culvert construction ensure that water flows easily and effectively through the system.

- **Side Walls**:

Corrugated box culverts' side walls are a crucial part of the structure, performing a dual function by combining structural robustness with hydraulic effectiveness. The design and purpose of these walls, which join the crown and inverts to form the culvert's sides and are crucial to maintaining the overall efficiency and durability of the construction, are crucial. Through their resistance to diverse external stresses, side walls perform a crucial structural role. They are made to bear pressure from the water inside the culvert as well as lateral stresses from the earth around it and traffic loads from cars driving over it (Sargand et al., 2018). The culvert system's stability and integrity are guaranteed by the sturdy structural design, which guards against bending, cracking, or collapsing. For instance, engineers calculate loads based on variables like soil characteristics, predicted traffic loads, and potential water pressure. By using these calculations as a reference, the proper wall thickness, reinforcing, and material strength are chosen, guaranteeing that side walls can support the applied loads without jeopardizing safety.

Besides, the side walls of the culvert have a vital hydraulic role in preserving the correct flow cross-section. They control and direct the flow of water or other fluids, preserving the hydraulic efficiency of the culvert. A culvert's side walls should be properly built to reduce turbulence, shield off impediments, and support free flow (Kolerski & Wielgat, 2014). The dimensions and shape of the side walls are carefully taken into account during the design phase to maximize hydraulic performance. The geometry of the entire culvert as well as the angle at which the side walls meet the inverts and the crown affect the flow characteristics. For the purpose of optimizing the side wall design and preventing excessive energy loss or turbulence, engineers use hydraulic modeling and simulations.

- **Wings**:

Wings serve a vital role in guiding the flow of water into and out of the culvert, mitigating the risk of erosion and facilitating efficient hydraulic performance. By projecting into the embankment or surrounding terrain, these side wall expansions increment the duct framework's general handiness and strength. The capacity of wings to control the progression of water into and out of the duct is one of their fundamental purposes. By extending beyond the confines of the culvert, wings assist in directing water into the entrance of the culvert and away from the exit. Properly constructed wings reduce the likelihood of water bypassing the culvert, which can result in erosion and damage to the surrounding area. Wings are essential for preventing erosion near the culvert. Water can convey silt and harm the ground downstream when it leaves the duct. Wings act as a cradle, scattering the energy of the streaming water and bringing down its true capacity for disintegration. This guard is essential in circumstances where disintegration can jeopardize the duct's primary trustworthiness or adjoining foundation.

A powerful wing configuration guarantees that water streams effectively into and out of the course, bringing down the possibility of flooding during times of extreme precipitation. Wings help to keep up with ideal stream limit and reduce ecological mischief by keeping water from ponding or overtopping the course (Kolerski & Wielgat, 2014). Engineers consider components including expected stream rates, the math of the duct, and the elements of the encompassing geology to enhance wing plan. To ensure that water moves through the duct successfully and securely, pressure driven models and reproductions assist with changing wing aspects and points (Kolerski & Wielgat, 2014). Consequently, wings are pivotal pieces of layered box courses that play out different errands, like stream bearing, disintegration aversion, and flood moderation. Appropriate design and integration into the culvert system are necessary for the culvert to function effectively and last a long time, as well as for the ecosystem that surrounds it.

B. Design Principles

- **Hydraulic Efficiency**:

Hydraulic efficiency is an essential component of the design of corrugated box culverts in order to reduce potential issues like flooding, erosion, and turbulence while simultaneously ensuring that water is conveyed effectively (Taylor & Singleton, 2014). A careful comprehension of various boundaries, including stream rates, stream speeds, and the cross-sectional state of the course, is important to accomplish water powered proficiency. Designing experts presently have a significant device for investigating and improving the presentation of ducts under different stream situations: hydraulic computational modeling

The careful assessment of the duct's pressure driven limit is the most vital phase in guaranteeing water powered effectiveness. The idiosyncrasies of the watershed and provincial precipitation examples could influence stream rates, which are analyzed by fashioners. These flow requirements are carefully taken into account when designing the cross-sectional shape of the culvert, including the sizes of the crown and inverts (Taylor & Singleton, 2014). The goal is to make sure that there isn't too much turbulence or restriction when water is being transported through the culvert.

Controlling flow velocities inside the culvert is a crucial component of hydraulic efficiency. High speeds can cause the culvert and surroundings downstream to erode, potentially resulting in structural damage. On the other hand, too low velocities may result in the deposition of sediment and a reduction in the conveyance capacity. In order to estimate the ideal cross-sectional dimensions and slope of the culvert, engineers compute the maximum permissible flow velocities using the laws of fluid mechanics (Conesa-García & García-Lorenzo, 2013). Engineers routinely use computational hydraulic modeling to improve culvert design and guarantee hydraulic efficiency under various conditions. These sophisticated simulations provide accurate design revisions by using mathematical models to estimate how water will flow through the culvert under various circumstances (Duncan et al., 2015). By taking into account variables like flow patterns, velocities, and pressure distributions, hydraulic modeling can shed light on possible trouble locations and the overall performance of the hydraulic system.

Tables, graphs, or numerical outputs can be used to present data gathered during hydraulic modeling. For instance, graphs can display velocity profiles while tables can provide flow rates at various culvert depths. This type of data visualization helps with the evaluation of hydraulic efficiency by assisting designers in identifying places that need to be modified to improve culvert performance. Therefore, in the construction of corrugated box culverts, hydraulic efficiency is of utmost importance. To ensure efficient water conveyance while reducing turbulence, erosion, and floods, it necessitates careful consideration of flow rates, velocities, and culvert shape. Insights into performance under various conditions are provided by computational hydraulic modeling, which improves the design process and eventually contributes to the successful and long-lasting operation of culvert systems.

- **Structural Integrity**:

For corrugated box culverts, structural integrity is a fundamental design element. It denotes the crucial necessity that the culvert system must endure varied applied loads in order to provide both safety and long-term functionality. These loads include the effects of hydrostatic pressure, soil pressure, and traffic pressure. When deciding on the size and composition of culverts, engineers do thorough load calculations and structural analysis, frequently using techniques like Load and Resistance Factor Design (LRFD). This ensures the structural stability of culverts. One step in ensuring structural integrity is a thorough analysis of the loads that will be placed on the culvert throughout its operational life (Damage-Resistant, 2018). For courses, these heaps are basically partitioned into three classifications: hydrostatic tension from water inside the course, soil powers applied by the encompassing earth, and traffic loads from vehicles crossing the duct. The load calculation process includes evaluating variables like the kind and volume of traffic, the density and characteristics of the surrounding soil, and the potential water levels inside the culvert.

The Load and Resistance Factor Design (LRFD) approach is one that is every now and again used to guarantee primary dependability. By including load decrease and wellbeing contemplations into the plan interaction, this approach empowers architects to consider load expectation vulnerabilities. Both the determined burdens and the duct materials' obstruction are considered by LRFD. By ensuring that the culvert can safely bear loads even in unfavorable conditions, LRFD fosters a high level of trust in its structural performance by taking into account uncertainties. To determine the best culvert dimensions, engineers look at factors like span length, wall thickness, and crown measurements. These plan standards are fundamental for ensuring the duct can proficiently convey loads and save primary soundness.

- **Material Selection**:

For corrugated box culverts, material determination is pivotal. The exhibition, cost-viability, and natural maintainability of the course are considerably affected by the decision between consistently utilized materials like layered metal and cement. This decision is reliant upon various components, including cost, strength, ecological effect, and venture explicit prerequisites. Corrugated metal is frequently chosen due to its low cost and straightforward installation (Aghniaey & Rodgers, n.d). For the majority of course applications, it offers a financially savvy elective, making it a helpful choice for projects with restricted subsidizing. Due to its structural strength and adaptability, corrugated metal is suitable for a variety of load conditions. Concrete, on the other hand, is extremely durable and resistant to corrosion. When the culvert must withstand harsh weather, such as saltwater or acidic chemicals, it is frequently chosen. Concrete culverts last longer and require less upkeep.

- **Geotechnical Considerations**:

In ridged box ducts, geotechnical examination is a major plan component since it is pivotal for evaluating and ensuring the security of the dirt that encloses and upholds the course structure. This examination incorporates an exhaustive assessment of various significant soil properties, like the dirt's conveying limit, settlement qualities, and vulnerability to disintegration.

Bearing Capacity: The ability of the earth to handle the loads imposed by the culvert, traffic, and outside factors is evaluated by geotechnical engineers. Calculations based on soil parameters including cohesion, friction angle, and density are made to determine if the soil can safely support the weight of the culvert and any additional applied loads.

Settlement Characteristics: The settling characteristics of the soil beneath the culvert are also taken into account in the analysis. Structure-related problems and uneven road surfaces can result from excessive settlement. Engineers estimate projected settlements and use techniques to reduce settling, such as soil compaction or the usage of foundation elements.

Erosion Potential: When water flows over or close to the culvert, a geotechnical study determines how susceptible the soil is to erosion. To prevent soil erosion, the design may include measures like the use of riprap or erosion control blankets. Geotechnical study provides crucial information that guides decisions about the foundation design and culvert support needs (Blanc, 2013). The culvert system is well-supported, robust, and able to endure the complex interactions between the structure and its surrounding soil when soil behavior and qualities are properly assessed and taken into account. In the end, this helps corrugated box culverts perform, last, and remain safe under a variety of geological and environmental situations.

- **Environmental Impact**:

In contemporary corrugated box culvert engineering, consideration of environmental effect has become a crucial design principle. Designers are putting more emphasis on minimizing these effects while guaranteeing effective water management because they are aware that the installation of culverts might have a negative influence on nearby ecosystems and aquatic habitats.

Mitigation Measures: Designers must include mitigation strategies that lessen the effect of culvert construction on the environment. These precautions include the inclusion of wildlife tunnels that allow animals to securely cross the culvert. In addition, erosion management techniques are used to stop silt from washing into surrounding waterways, maintaining both water quality and aquatic habitats.

Eco-Friendly Materials: Regarding the effects on the environment, the choice of materials becomes even more important. Engineers take into account materials that have a smaller carbon footprint and do less environmental harm over the course of their lifetime. To reduce corrosion and increase the lifespan of the culvert, this may entail using recycled or sustainable materials and using eco-friendly coatings.

Long-Term Sustainability: The construction and ongoing maintenance of the culvert are both necessary to ensure its long-term viability. The least amount of environmental damage is possible through routine inspections and maintenance procedures. To manage the ecological imprint of the culvert sustainably, these actions include vegetation maintenance, silt removal, and debris clearance (Blanc, 2013). Engineers can design corrugated box culverts that not only efficiently manage water flow but also blend in with the environment by taking environmental impact factors into account when designing them. This helps to promote a more environmentally friendly and sustainable approach to civil engineering.

2.6.2. Calculations and Analysis in Corrugated Box Culvert Design

Hydraulic Design:

- **Flow Analysis:** Flow analysis involves determining the expected flow rate (Q) through the culvert under various conditions, such as rainfall events. This calculation considers factors like catchment area, precipitation rates, and runoff coefficients.

- **Flow Velocity:** Flow velocity (V) within the culvert is essential to prevent erosion and maintain efficient conveyance. It's calculated using the flow rate and the cross-sectional area of the culvert: V = Q / A, where A is the cross-sectional area.
- **Cross-Sectional Shape:** The hydraulic efficiency is substantially impacted by the cross-sectional form. The ideal shape is determined through calculations and analysis that take into account things like flow capacity, velocity distribution, and sediment transfer. Circular, rectangular, and trapezoidal shapes are typical.

Using the Rational Method, the peak flow rate is calculated based on the catchment area and rainfall intensity. For instance, take a rainfall intensity of 2 inches per hour and a catchment area of 10 acres.

Peak Flow Rate (Q) = (Catchment Area in acres) x (Rainfall Intensity in inches per hour) / 96.23

Q = (10 acres) x (2 inches/hour) / 96.23 = 0.207 cfs

The selected culvert size should comfortably handle this flow rate.

Structural Design:

- **Load Analysis:** The structural loads on the culvert, such as traffic volumes and soil pressures, are assessed by load analysis. To make sure the culvert can take these forces safely, engineers compute the maximum anticipated loads and distribute them among its parts.

- **Material Strength:** Calculations of material strength determine if the chosen material (such as concrete or corrugated metal) can support the imposed loads without going over its structural limit. Analyzing elements like tensile and compressive strength is part of this process.
- **Reinforcement:** To improve the structural integrity of the culvert, reinforcement calculations are used to estimate the kind, number, and placement of reinforcements, such as steel bars or fiber-reinforced materials.

To ensure structural integrity, perform load calculations. For an H-20 vehicle loading, consider a concentrated load of 14,515.744 kgs.

Load Factor (F) = 1.25 (AASHTO LRFD)

Required Culvert Design Load (P) = Load Factor

(P) = Load Factor (F) x Vehicle Load = 1.25 x 14,515.744 kgs = 18,144.68 kgs

Geotechnical Analysis:

- **Soil Bearing Capacity:** The bearing capability of the soil surrounding and beneath the culvert is evaluated by geotechnical analysis. To do this, soil tests must be performed to ascertain variables like cohesiveness and friction angle. The calculations guarantee that the soil can sustain the weight of the culvert without experiencing excessive settlement or failure (Blanc, 2013).
- **Settlement Analysis:** The amount of vertical displacement that the culvert would incur as a result of soil compaction over time is predicted through settlement

analysis. It assists in determining whether additional steps are required to alleviate settlement issues, such as soil compaction or the use of deep foundations.

Example

Given a soil bearing capacity of 3,000 psf and the culvert's dimensions, calculate the total load applied to the soil:

Load on Soil (P_{load}) = Culvert Weight + Vehicle Load

Culvert Weight is calculated based on the weight of the selected 48-inch diameter corrugated metal culvert per unit length. For this example, we'll assume a length of 30 feet.

Culvert Weight ($W_{culvert}$) = Weight per Unit Length x Culvert Length

Assuming a weight of 226.796 kgs per linear foot for the selected culvert:

$W_{culvert}$ = 226.796 kgs/foot x 30 feet = 6,480.88 kgs

Now, calculate the total load on the soil:

P_{load} = 226.796 kgs + 14,515.744 kgs = 14,742.54 kgs

With a soil bearing capacity of 3,000 psf, the soil can comfortably support this load:

Soil Bearing Capacity (SBC) > P_{load}

3,000 psf > 14,742.54 kgs

The soil bearing capacity exceeds the applied load, indicating that the soil can adequately support the culvert.

Table 2.1. Design Parameters

Parameter	**Value**
Design Flow Rate (Q)	0.207 cfs
Culvert Length	30 feet
Culvert Material	Corrugated material
Soil Bearing Capacity	3,000 psf
Live load(P)	18,143.68 kgs
Selected Culvert Size	48-inch diameter

2.7. Design Practices and Guidelines Across the World

Corrugated box culverts are significant pieces of a common foundation from one side of the planet to the other, and their plan is administered by specific methodology and decides that are pertinent to local necessities and concerns (Blanc, 2013). The plan rules and methodology utilized in North America, Europe, and Asia are dissected exhaustively, with an accentuation on supportability and transformation put on fundamental standards, norms, and provincial contrasts.

- **North America**
- **AASHTO Guidelines (American Association of State Highway and Transportation Officials)**:

Culvert configuration practices in North America, notably in the US, are significantly affected by the American Association of State Highway and Transportation Officials (AASHTO) rules. These suggestions offer an intensive structure for the plan of ridged box courses, including many vital components that are urgent for ensuring the security, viability, and strength of the transportation foundation (Rossini et al., 2020). Course configuration depends on the "LRFD Bridge Design Specifications" by AASHTO, which show a commitment to demanding design and flexibility.

With regards to culvert design, the AASHTO suggestions and recommendations are intensive. They cover every fundamental part, from the selection of materials to the structure prerequisites. Designers will constantly approach intensive guidelines because of this exhaustive procedure (Rossini et al., 2020). The guidelines offer advice on how to choose the right materials, taking into account factors like durability, resistance to corrosion, and affordability. This counsel assists engineers with picking materials that fit the task's remarkable necessities and monetary impediments.

Additionally, effective water management is a key component of culvert design, and the AASHTO recommendations cover hydraulic aspects in great detail. These recommendations help engineers identify the anticipated flow rates, speeds, and cross-sectional patterns that maximize hydraulic efficiency. As a result, culverts effectively control water flow without contributing significantly to erosion, floods, or excessive turbulence (Rossini et al., 2020). Additionally, culvert design must prioritize structural integrity due to the necessity to endure a variety of stresses, such as traffic loads and soil pressures. The Load and Resistance Factor Design (LRFD) principles are emphasized in AASHTO's recommendations. Engineers are able to take into consideration design parameter uncertainties thanks to LRFD, which integrates safety factors and probabilistic approaches. With this method, resilient culvert systems that can endure a variety of potential loading conditions are produced.

The rules also cover construction parameters, offering precise and standardized directions for corrugated box culvert installation. By maintaining uniformity in construction methods, the possibility of mistakes or variances that can impair performance is reduced and culverts are built in accordance with the required design criteria. AASHTO's culvert design rules are critically dependent on the adoption of LRFD concepts (Rossini et al., 2020). The many load combinations and uncertainties in the loading and material qualities are taken into account using the current and reliable approach known as LRFD. Engineers ensure that the culvert can safely resist weights under a variety of scenarios by accounting for these uncertainties, improving safety and reliability.

The adaptability of the AASHTO rules is one of their advantages. These rules can be used by engineers in a variety of situations, from urban settings to isolated rural places. Engineers may create context-specific designs thanks to this adaptability, ensuring that the culvert is suitable for its intended use in the project's particular geographical and climatic setting (Rossini et al., 2020).

- **LRFD Principles (Load and Resistance Factor Design)**:

The foundation of North American culvert design is based on the Load and Resistance Factor Design (LRFD) concepts, which provide a methodical and logical way to guarantee that culverts are not only structurally sound but also economical, resilient, and secure. As they direct the design process to consider different burdens mixes, vulnerabilities, and material characteristics, these ideas are unequivocally imbued in designing techniques.

Consideration of Multiple Load Combinations

One of LRFD's fundamental ideas is taking into account a wide variety of load combinations. When designing culverts, engineers must take into account a wide range of stresses, such as vehicle loads, soil pressures, hydrostatic forces, and seismic effects. The place of the duct and the progression of traffic are two instances of factors that could incredibly influence these heaps (Rossini et al., 2020). Using LRFD principles, engineers can evaluate and combine these loads in a systematic manner to ensure that the culvert can withstand a variety of conditions.

Accounting for Uncertainties

Engineering is rife with uncertainties, and LRFD principles offer a way to efficiently deal with them. Engineers must deal with unknowns in loading conditions, material qualities, and other factors when designing culverts. By including safety factors in the LRFD that take these uncertainties into account, the culvert's structural integrity and safety are designed with a better degree of assurance.

Cost-Effective Designs

By matching the degree of conservatism with the degree of uncertainty, LRFD supports economically sound culvert designs. Instead of employing predefined safety factors, LRFD uses probabilistic approaches to assign various load and resistance components varying factors. This indicates that while factors for less certain components of the design may be higher to provide greater safety margins, factors for more definite aspects may have lower factors, resulting in cost savings.

Resilience and Longevity

Culvert system durability and resilience are greatly enhanced by LRFD concepts. Engineers create culverts that are better prepared to withstand unforeseen events like extreme weather, increasing traffic loads, or changes in soil conditions by methodically taking into account various loading scenarios and accounting for uncertainties. As a result, culvert systems last longer and need fewer repairs or replacements in the long run.

Safety Assurance

Safety is paramount in culvert design, as failures can have severe consequences for both infrastructure and public safety. By carefully analyzing loads and using probabilistic approaches, LRFD principles guarantee that culverts are designed with a high level of safety. Specialists can dependably ensure that courses are equipped for enduring cruel circumstances and meet or outperform wellbeing guidelines. In this manner, in North American duct plan, the Load and Resistance Factor Design (LRFD) standards are basic. They offer an arranged and purposeful system that considers different burden designs, vulnerabilities, and material qualities. As well as further developing security, LRFD empowers course frameworks that are strong, versatile, and appropriate to the wide assortment of issues that traffic foundation might experience. Even as infrastructure requirements shift, LRFD principles remain an essential tool for ensuring the dependability and efficiency of culverts in North America and elsewhere.

- **Europe**
- **CEN Standards (European Committee for Standardization)**:

The European Committee for Standardization (CEN) principles are utilized in Europe, where there are a wide range of sorts of scenes and transportation frameworks, to make a uniform starting point for course plan and development among its part countries (CHBDC, 2018). The consistency and nature of course constructing projects all through Europe are fundamentally influenced by these norms, which cover an extensive variety of duct configuration related points.

A Unified Framework

The mainland's broad organization of interstates, rail lines, and waterways regularly crosses a few countries. To guarantee that transportation framework can undoubtedly span global boundaries, CEN offers a typical language and set of rules that immediate the plan and development of ducts all through these different areas.

Comprehensive Coverage

CEN principles incorporate each feature of culvert design. They incorporate significant points such development strategies, foundational layout, pressure driven execution, and materials. Specialists and creators will have a strong arrangement of standards to observe at each phase of the course's life cycle, from wanting to execution, because of this broad inclusion (CHBDC, 2018).

Materials Selection

CEN standards offer recommendations to the determination of materials utilized in duct development. These ideas consider components including heartiness, influence on the climate, and topographical availability. CEN guarantees that courses all through Europe meet uniform quality and execution guidelines by normalizing material choice.

Structural Design

The CEN principles' underlying model standards ensure that courses can deal with the large number of burdens they can insight. These loads can vary greatly, depending on factors like the environment in rural areas or heavy traffic on major roads (Amir Ablahad & Rasslan, 2023). The plan determinations, wellbeing contemplations, and burden blends indicated by the norms work on the underlying uprightness of courses.

Hydraulic Performance

For culverts, effective water management is essential, and the CEN standards cover hydraulic performance in great detail. These guidelines offer direction on variables like flow rates, speeds, and culvert geometry. CEN guarantees that culverts properly manage water flow, reducing the risk of floods and erosion. This is done through optimizing hydraulic efficiency.

Quality Assurance

CEN standards play a pivotal role in quality assurance for culvert construction. Contractors and engineers may confidently produce projects that meet or surpass European requirements for safety and performance by upholding these norms (Amir Ablahad &

Rasslan, 2023). For infrastructure projects receiving funding from the European Union, where adherence to CEN standards may be necessary, this quality assurance is especially crucial.

- **Emphasis on Sustainability**:

Environmental concerns and sustainability are becoming more and more important in European culvert design. The use of environmentally friendly materials, the installation of fish-friendly culverts, and planning with the least amount of ecological impact are now commonplace. The dedication to sustainability in Europe is consistent with its more general objectives of environmental preservation and responsible infrastructure development.

- **Asia**
- **Japan's MLIT Guidelines (Ministry of Land, Infrastructure, Transport and Tourism)**:

Japan places a premium on resilient infrastructure because it is located in an area prone to earthquakes and typhoons. The Ministry of Land, Infrastructure, Transport and Tourism (MLIT) rules for culvert design in Japan address a range of important issues, including as hydraulic efficiency, structural integrity, and seismic resilience (Jeong et al., 2018). These exacting requirements are necessary to make sure that culverts can resist the difficulties presented by Japan's unstable natural environment.

The MLIT recommendations are well known for their thorough approach to culvert design. They cover every aspect of design and construction, leaving no stone untouched. With this method, culverts are guaranteed to be resilient to a variety of loading situations and environmental difficulties in addition to being effective at controlling water flow. In addition, effective water management is crucial in Japan because of the country's frequent flooding, typhoons, and severe rains (Jeong et al., 2018). The MLIT standards offer suggestions for enhancing the designs of culverts so that water can flow smoothly. This decreases the opportunity of disintegration and floods during serious climate occasions.

Furthermore, the seismic activity in Japan requires a strong underlying design for culverts. The principles join state of the art seismic designing procedures to ensure that courses can get through quake related ground aggravations. Indeed, even in the toughest spots, underlying trustworthiness is kept up with. Japanese designing is likewise known for its seismic heartiness, and duct configuration goes with the same pattern (Jeong et al., 2018). Current strategies are utilized to expand a duct's ability to endure seismic energy without forfeiting usefulness, like adaptable joints and built-up materials.

The MLIT guidelines facilitates culverts design that can be modified to accommodate the impacts of cataclysmic events in Japan. Engineers consider the likely impacts of tremors, tidal waves, and hurricanes to ensure that courses are protected and useful even after such catastrophes. Thus, with regards to course plan, where vigor and transformation are critical, Japan's MLIT rules are the best quality level (Jeong et al., 2018). These guidelines make infrastructure that not only manages water effectively but also withstands earthquakes and other extreme weather conditions, ensuring the safety and functionality of the nation's transportation networks. They do this by integrating progressed seismic designing practices and tending to the unique difficulties presented by Japan's common habitat.

- **India's BIS Codes (Bureau of Indian Standards)**:

India relies on the Bureau of Indian Standards (BIS) regulations for culvert design due to its vast and diverse geographic terrain. These codes provide a well-organized framework that includes requirements for building materials, structural design, and construction methods. They are crucial in a nation with a variety of climates, from desert landscapes in some areas to intense monsoon rains in others (Jeong et al., 2018). BIS standards offer precise suggestions for culvert design that are comprehensive and area specific. This specificity is essential in a nation where regional variations in soil types, rainfall patterns, and climatic circumstances are common. BIS regulations guarantee that culvert designs are acceptable and effective by adapting recommendations to local conditions.

One major strength of BIS codes is their versatility. These programs can be used by engineers to develop context-specific designs that take into account the particular difficulties provided by India's diverse topography. BIS codes are an invaluable tool for engineers working across the nation, whether they are building culverts to survive the arid conditions of desert regions or to withstand heavy monsoon rains. Additionally, due to India's size, there are a variety of soil types and rainfall patterns. BIS standards recognize these regional differences and provide recommendations on elements like material choice and structural design that are suited to the unique requirements of each region. With this method, culverts are guaranteed to be resilient to regional problems in addition to being functional.

- **Adaptability and Context-Specific Design**

Corrugated box culvert designs all throughout the world share a common concept of adaptability and context-specific design. Globally, culvert engineers and designers are aware that there is no one size that fits all solutions for these essential infrastructure elements. They take into account the unique regional difficulties, meteorological circumstances, and environmental considerations that affect each project (Jeong et al., 2018). This adaptability is a reaction to the wide range of issues encountered globally. In Japan's earthquake-prone regions, where culverts must not only control water but also withstand ground changes, engineers must take seismic activity into account. Culvert designs that reduce ecological effect and advance environmental harmony are strongly encouraged in Europe. Culvert systems in India must be strong enough to withstand the severe monsoons that are typical of the region.

Additionally, adaptability guarantees that culvert systems are well-suited to their specific situations in addition to being functional. It emphasizes the significance of customizing culvert designs to fit the unique difficulties and requirements of each region and demonstrates a dedication to efficiency, safety, and environmental responsibility. Ultimately, the durability and efficiency of these vital infrastructure elements around the world are influenced by the adaptability of culvert design.

2.8. Conclusion

In conclusion, corrugated box culvert design and analysis are key components of civil engineering that enable effective water management and secure traffic infrastructure all over the world. The many facets of culvert design were examined in this research, including structural components, hydraulic effectiveness, material selection, geotechnical considerations, and environmental effects. Culvert design rules and procedures are firmly established in both local requirements and international norms. The AASHTO guidelines and LRFD principles are used in North America, whereas CEN standards are used in Europe to standardize methods and place a stronger emphasis on sustainability. Prioritizing seismic resilience and flexibility, Asia, in particular Japan and India, navigates its special problems through MLIT guidelines and BIS rules, respectively.

Adaptability and context-specific design are frequent themes in culvert design that cross international boundaries. Engineers are aware of how important it is to adapt designs to local conditions in order to maximize culvert systems' performance and durability. Culvert design continues to be at the forefront of engineering innovation as the world struggles with changing climatic patterns and environmental requirements. The future of culvert systems promises not just effective water management but also a sustainable, resilient, and ecologically responsible approach to civil engineering by embracing technological breakthroughs and holistic design principles. Through this comprehensive investigation, we imagine a time when culverts effortlessly combine environmental stewardship with functionality, protecting our infrastructure and the environment for future generations.

CHAPTER 3 DEVELOPMENT OF A TWO-DIMENSIONAL FINITE ELEMENT MODEL FOR CORRUGATED BOX CULVERTS

3.1. Introduction

Corrugated box culverts have become popular in recent decades as they were designed with the purpose of fulfilling the requirement for a structure that can offer a wide space despite limited height clearance. They are an effective and economical alternative to short-span bridges because of their durability, reliability, lightweight, and construction. Also, they can meet the design and safety requirements for traditional bridges with low initial and long-term maintenance costs. The structural strength of the culvert is more as it has a deep corrugated structural plate, which provides stiffness to the culvert. Hence, it helps to prevent excessive deflections from occurring during backfill and to improve buckling resistance. Figure 3.1 shows a corrugated box culvert profile under construction.

Figure 3.1 A corrugated box culvert profile under construction (Sweden 2006).

The performance of buried corrugated box culverts is influenced by the characteristics of both the structure itself and the surrounding soil, leading to interactions between the two. This type of relationship between the two is commonly known as soil-structure interaction.

Most of the studies were focused on the short-term performance under backfilling and static loads. A series of full-scale tests were carried out by Byrne (1978), McCavour et al. (1998), Manko and Beben (2005), Morrison (2005), Lougheed (2008), and Flener (2010) to study the behavior and performance of the structure during backfilling.

Due to the high demand of CBCs, their complex response during backfilling and associated soil-structure interactions has not been fully understood. However, by using finite element (FE) techniques, researchers can perform numerical studies to analyze changes in the behavior and performance of the structure under varying conditions. To understand the soil-structure interaction, researchers often observe the actual behavior of the buried structure and compare it to calculations obtained through finite-element analyses (Moore and Brachman, 1994; Webb et al, 1998; Moore and Taleb, 1999; Kim and Chai,2005; Kunecki, 2006; Kitane and McGrath, 2006; Bayoglu Flener, 2009). Analysis of a corrugated box culvert can be used to determine the stability of the structure, optimize the design of the culvert, and assess the effects of different loading conditions on the system.

In recent years, two-dimensional (2D) finite element (FE) modelling has been used to explore the structural integrity of a corrugated box culvert (CBC). It is widely used for the design and analysis of corrugated box culverts, as a numerical method is used for finding approximate solutions for complex structures. However, several factors such as the backfill soil stiffness, the soil cover, and the trench geometry, including the trench width and the trench side slope that may affect the complex soil structure interaction of Corrugated Box Culverts (CBCs) for longer spans are not yet fully understood. This paper presents the performance of the corrugated box culvert, which studies the several factors such as the stiffness of the backfill soil, soil cover depth, width of the trench, trench side slope that may significantly affect the thrusts and bending moments developed in the structure. Hence, a two-dimensional finite element model of a field case study of a long-span box culvert in Lidköping, Sweden, was developed using the Plaxis 2D software. The developed model was then verified against the data recorded in the field. Finally, a comprehensive parametric study was conducted to investigate the effect of the backfill stiffness, soil cover depth, culvert span and trench geometry on the thrusts and bending moments resulting from the backfilling process.

3.2. Case study review

The full-scale field tests on box culvert carried out by Bayoglu Flener at Lidköping, Sweden are considered here for validation of the new, 2D model. Specifically, the box culvert is modelled during backfilling, using the approach described in the following sections. The analysis was used to determine the performance of the structure during backfilling and to verify the reliability of the proposed model. The backfill soil used is a coarse-grained material whose strength is greatly affected by its degree of compaction, and its properties were obtained through tests conducted at both the site and laboratory. The backfill soil has been placed in layers of about 300-350 mm thick and each layer was compacted by six passes of 500kg compactors up to 4.073m height (providing a cover of 0.45 m above the crown). The box culvert was monitored during the backfill process until the backfill reached 0.45 m above the crown. Figure. 3.2 shows some stages of the construction and backfilling. The strain gauges were installed to record the strain in the bridge's longitudinal direction. Potentiometers and LVDTS were used to measure the vertical displacements at the crown, the middle of the haunch, and the footing (see figure 3.3).

Figure 3.2. (a) Assembling of the box culverts and (b) compaction of the backfill

Figure. 3.3 Strain gauges and the displacement measurements at the corrugated haunch area; LVDT for the 14 m span structure

3.3 Numerical details

3.3.1 Geometry

Figure 3.4 illustrates the geometry of the deep-corrugated box culvert. The culvert is built up of essentially two elements, the corrugated flexible conduit (corrugated steel plates) and the surrounding soil. The numerical model developed has a span length of 14m, and an inside rise of 2.4m, with a trench side slope of 1V:1.5H. The rise/span ratios and top radius to side radius ratios were 0.2 and 11.3 for the 14 m span culvert. The soil cover depth considered in this case was 0.45m. To minimize the boundary effect, the two external lateral boundaries are located approximately 40 m in length apart and a bottom boundary 10 m in depth is provided below the initial ground surface of the considered field test. Two concrete footings were modeled as elastic, each 1m wide and 0.25 m thick were constructed with an elastic modulus (E) of 45 Gpa and poison's ratio of 0.3. As the groundwater table was below the culvert base, the water table effect was not considered in this case.

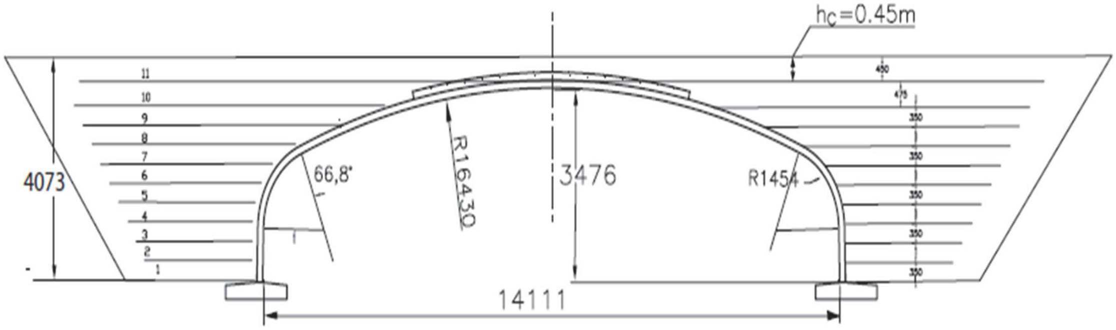


Figure 3.4. geometry of the deep-corrugated box culvert.

3.3.2 Corrugated steel plates

The box culvert was fabricated from deep-corrugated plates with a wavelength of 381 mm, corrugation depth of 140 mm, and plate thickness of 7 mm. The average yield strength for the plate material was 352 Mpa. The area of the plate was found to be 9.81 mm2/mm. Table 3.1 shows the dimensions and steel properties of the culvert. Figure 3.5 shows the corrugated steel profile used in the FE model.

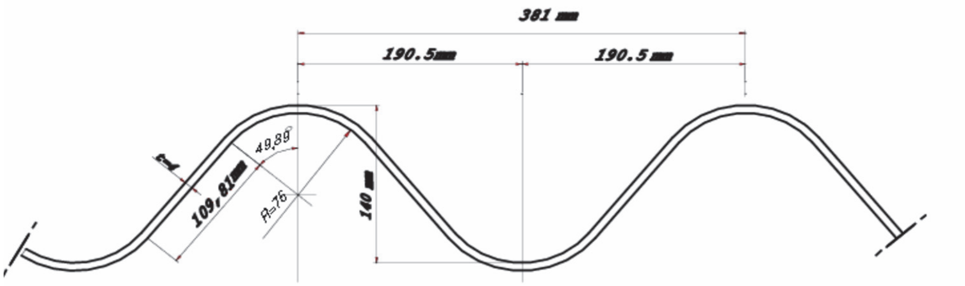


Figure 3.5. Corrugated steel profile

Table 3.1. Dimensions and Steel Properties of the 14 m span culvert

Properties	**Units**	**Corrugated Steel plate**
Plate thickness, t	mm	7
Elasticity Modulus, E_{st}	Gpa	205.7
Cross sectional area, A	mm^2/mm	9.8
Cold formed yield strength, f_{yk}	MPa	352
Moment of Inertia, I_{st}	mm^4/mm	22,856
Section modulus, W	mm^3/mm	296

3.3.3 Backfill and soil properties

The surrounding soil can be categorized into two types: the foundation soil below the structure, and the backfill soil close to the culvert. The Hardening Soil with a small strain model was used to model the soil behaviour, which stimulates the soil stress-strain behaviour of non-linear and stress-dependent soils. The model used is a hyperbolic type of elastoplastic model that includes compression to stimulate the compaction of soil during primary compression. In addition, the HS soil model yields accurate stiffness variations for small strains during the backfilling process. Compacted soil was used as the backfill soil surrounding the box culvert, which was compacted in layers; each layer was 300 mm height. Table 3.2 summarizes the properties of the backfill and subgrade soils.

Table 3.2 Properties of Backfill and Subgrade materials

Parameter	**Units**	**Backfill soil**	**Subgrade soil**
Dry unit weight, γ_{dry}	kN/m3	18.5	19
Saturated unit weight, γ_{sat}	kN/m3	21	21
Secant stiffness in standard drained triaxial test, E_{50}^{ref}	kPa	60	40
Tangent stiffness for primary oedometer loading, E_{oed}^{ref}	kPa	60	40
Unloading/reloading stiffness, E_{ur}^{ref}	kPa	180	120
Cohesion, c′ (kPa)	kPa	2	2
Internal friction angle, φ′	Deg.	40	40
Dilatancy, ψ	Deg.	10	10
Power for stress-level dependency of stiffness, m		0.5	0.5

3.3.4 Mesh

For the FE model, 15 node triangular elements were selected to stimulate the soil layers and the culvert. After the mesh coarseness was set to fine, the developed FE model comprised approximately 7500 elements and 60500 nodes. Figures 3.5 and 3.6 illustrates the undeformed mesh and mesh formulation of the two-dimensional FE model. The friction behaviour at the culvert-soil interface and the interaction between the concrete footings and soil layers were stimulated using five node interface elements from the Plaxis library and a strength reduction factor, R_{inter} of 0.67 was used to model the roughness of the interaction.

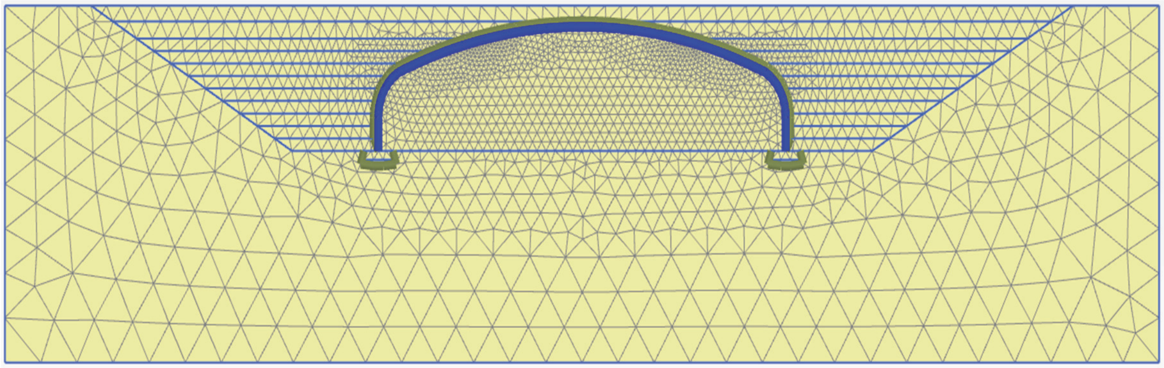


Figure 3.5. Undeformed mesh of the two-dimensional FE model

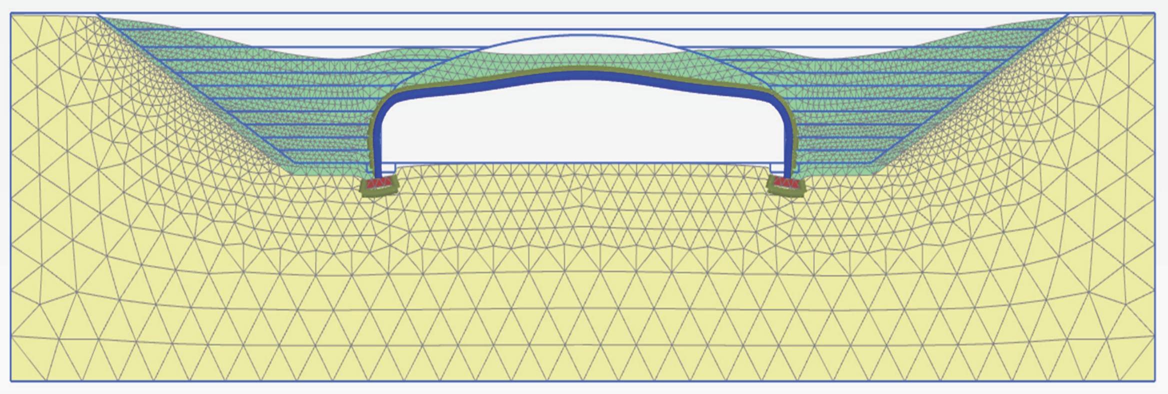


Figure 3.6. Mesh formulation of the two-dimensional FE model

3.3.5 Boundary conditions

The boundary conditions were set to be fixed in the horizontal direction and free in the vertical direction. In the model, fully fixed boundary conditions were constructed at the base for static analyses, while the lateral boundaries were set as free in the vertical direction and fixed in the horizontal direction.

3.3.6 Staged construction

The construction sequence stages for the calibrated FE model were stimulated in the 2D modelling. The initial stage was performed by the K0 technique, where initial geostatic in-situ stresses were established. The groundwater table was not considered as it was assumed to be below the culvert profile. The second stage stimulates the excavation of the ground to the proposed foundation level by deactivating the existing soil in the region, which determines the changes in stresses and strains due to the excavation. The third stage stimulates the construction of the box culvert by activating the steel plate elements, the surrounding interface, and the bedding material.

During backfilling, the soil is placed on either side of the box culvert and the compaction in successive layers, which is typically about 300 mm thick up to the proposed height (0.45 m above the crown). In the subsequent stages, the backfilling process is stimulated by implementing the described compaction efforts. At the start of backfilling, displacements are set to zero to capture the deformations resulting from the backfilling process. The layers are sequentially activated with their corresponding surface load, which is then deactivated in the following stage, and the next layer and its load are subsequently activated, continuing until the compaction process is finished. Figure 3.7 illustrates the simulation of the compaction process.

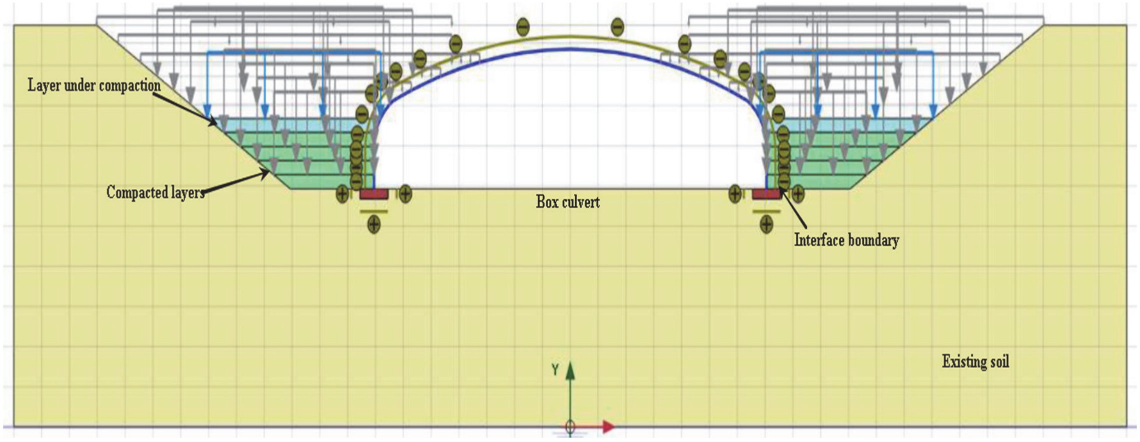


Figure 3.7. Simulation of the compaction process.

3.4 Results and Discussion

The results of vertical displacement, thrust and bending moment obtained from the HS material model are very similar to the deformation, thrust, and bending moment from the field measurements.

3.4.1 Crown Deformation

Figure 3.8 shows the model results for vertical deflections during backfilling with a 0.45 m cover. It is evident that the results of vertical displacements obtained from the HSs material model and that from field measurements are similar. Both curves show how the culvert rises as a consequence of the lateral earth pressure. During backfilling, the crown tends to rise due to the increasing lateral pressure from the soil, but rising usually ceases before the backfill attains the top of the crown arch. The maximum crown displacement appears at the crown of the box culvert just like at the field. After the layer 3.15 m, the culvert reverses its movement from upwards to downwards which is also observed at site. The numerical analysis yields a maximum crown rise of 20 mm when backfilling at the crown level, as compared to 17 mm recorded in the field.

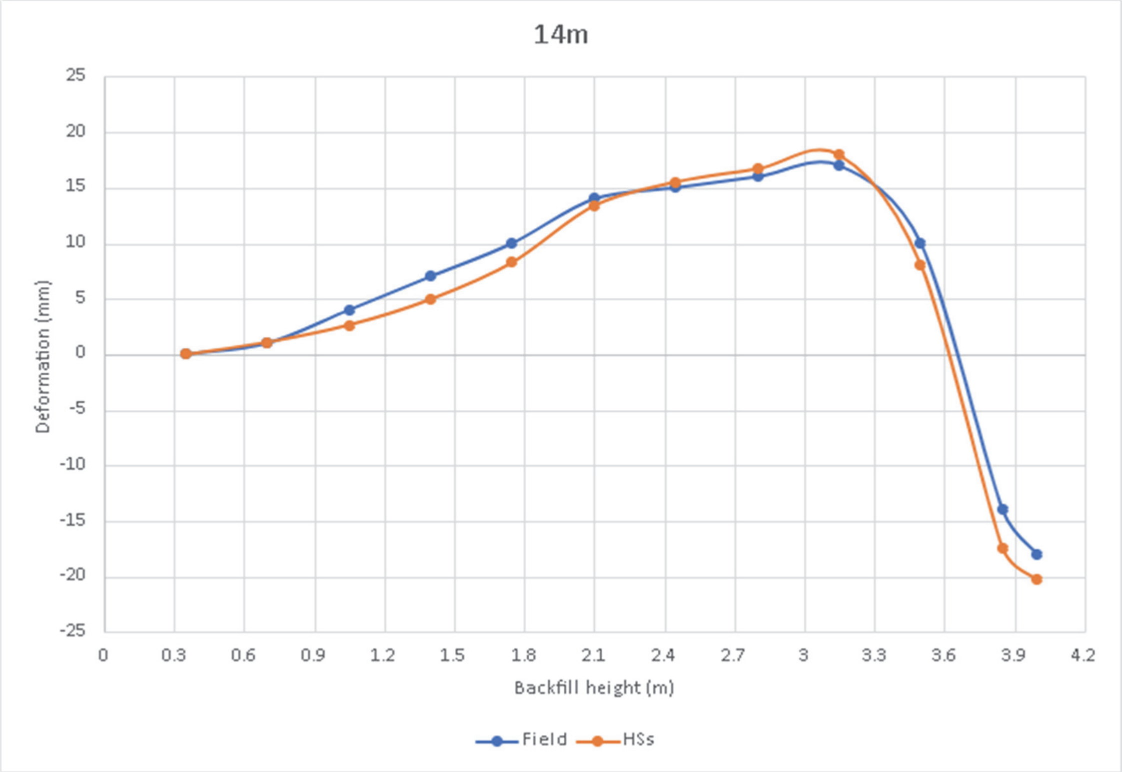


Figure 3.8. Vertical displacements of the top of the crown arch during backfilling

3.4.2 Bending Moment

The line graph shown in Figure 3.9 compares the bending moment at the crown during backfilling over each backfill layer. It is noticed that the magnitude of the bending moment at the crown decreases gradually and increases after the backfill height passes the crown level. The maximum negative bending moment of -12.58 kN.m/m and -12.50 kN.m/m was observed at the crown as the backfill layers reached the crown level for numerical analysis and filed measurement, respectively. The numerical model successfully calculated the bending moments similar to the bending moments measured from the field.

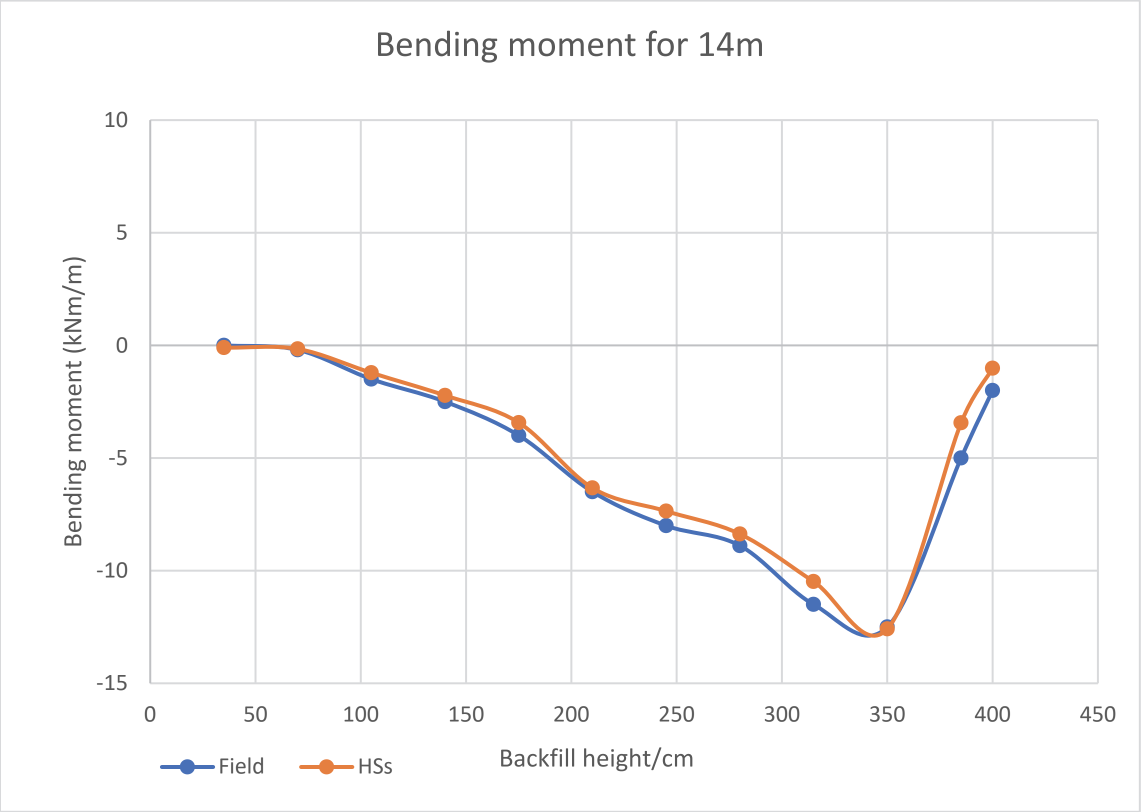


Figure 3.9. Bending moments at the crown location during all stages of the backfilling.

3.4.3 Thrust

Figure 3.9 shows the thrusts at the crown upon completion of backfilling up to 0.45 m cover. From the graph, the thrust shows a downward curve (gradually decreasing) as the backfill height increases to 4.073 m. The maximum compressive forces after completion of the backfilling observed at the crown arch were –209.9 kN/m and -210.0 kN/m for numerical analysis and the field study, respectively. Results from the two-dimensional FEM match relatively well with the results measured from the field at the crown location.

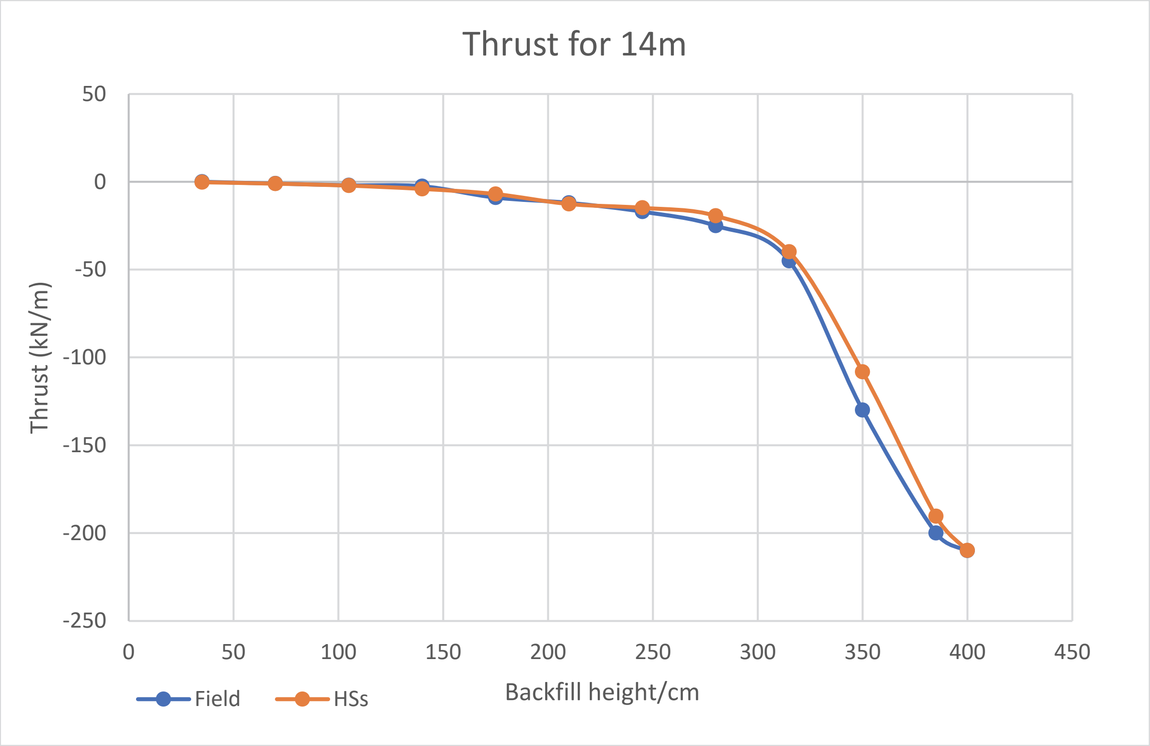


Figure 3.9. Thrusts at the crown during backfilling.

3.5 Conclusions

This chapter presented findings based on full-scale monitoring of a 14 m span box culvert during backfilling in Lidköping, Sweden. The mechanical response of the box culvert was calculated using two-dimensional analysis. The following conclusions are made:

1. The HS soil model accurately aligned with the field data recorded for the crown deformation, bending moment, and thrusts of the box culvert during backfilling. Hence, the HS soil model provides a more rational and realistic model for assessing the soil-structure behaviour and the associated mechanical response parameters.
2. The crown deformation, bending moment, and thrusts obtained by the 2D FE model are closely adhered to those measured in the field.
3. The observed performance of the developed two-dimensional finite element model is considered for proceeding with a parametric study in the following chapters.

CHAPTER 4 SOIL STRUCTURE INTERACTION OF CORRUGATED BOX CULVERT

4.1 Introduction

This chapter presents results from the parametric studies for corrugated box culverts. The parametric study was based on two-dimensional finite element analyses, which were carried out using the software package Plaxis 2D. Plaxis 2D is a computer program that analyzes stability and deformation in various geotechnical applications, using two-dimensional finite element analysis. It provides a sophisticated analysis of soil behaviour, unlike many other simplified programs. Therefore, Plaxis 2D was chosen to model the interaction between a flexible culvert structure and soil. The program offers several theories such as Mohr-Coulomb, Hardening Soil Model, and soft soil creep soil. The best feature of the software is its ability to model backfilling tests with the ability to change material properties, boundary conditions, and loads in each predetermined phase.

The purpose of the study was to determine the crucial parameters governing the behaviour and performance of the corrugated box culvert. Specifically, four parameters were varied: trench width, trench side slope, soil cover depth, and the backfill soil stiffness of soil-structure interface. Each parameter is investigated in terms of its effects on crown deformation (after peaking and compaction), thrusts, and bending moments at crown, haunch, and footing in three different spans of culverts (7m, 14m, and 28m) during backfilling.

4.2 Finite Element Model

A finite element model is a mathematical representation of a physical system that uses complex algorithms to simulate its behaviour under different conditions. Soil-structure interaction of corrugated box culverts during backfilling were analyzed numerically by utilizing the software PLAXIS 2D 2021. The backfilling process is simulated by assigning different construction phases for the soil elements in the software. FEM simulation enables a detailed assessment of the magnitude and distribution of mechanical parameters throughout the modeling process. The analysis used the calibrated model to conduct parametric studies to investigate changes in the performance of the corrugated box culverts when the key parameters are varied. To create a model in Plaxis 2D, the first step is to design the geometry, which includes points, lines, and clusters. Plate elements are then used to represent the behaviour of walls, plates, and shells. These plates serve as structural components that produce slender structure with high flexural rigidity EI and axial stiffness EA. The software enables the interface to define interaction between the soil and structure.

4.3 Numerical details

4.3.1 Geometry

In order to study the behaviour and performance of culverts, corrugated box culverts with three different spans (7 m, 14 m, and 28 m) and heights were modelled in Plaxis 2D. The cross-sectional view of three box culverts with 7 m, 14m, and 28 m span are shown in Figure 4.1. Table 4.1 provides the geometry of the culverts for 7m, 14m, and 28m spans. The study involved developing a total of twelve models, each varying in terms of trench width, trench side slope, soil cover depth, and backfill soil stiffness. The steel structure used was corrugated steel plates of type SuperCor S37. Two concrete footings, each 1m wide and 0.25 m thick were constructed with an elastic modulus of 45 Gpa. As the groundwater table was below the culvert base, the water table effect was not considered in this case.

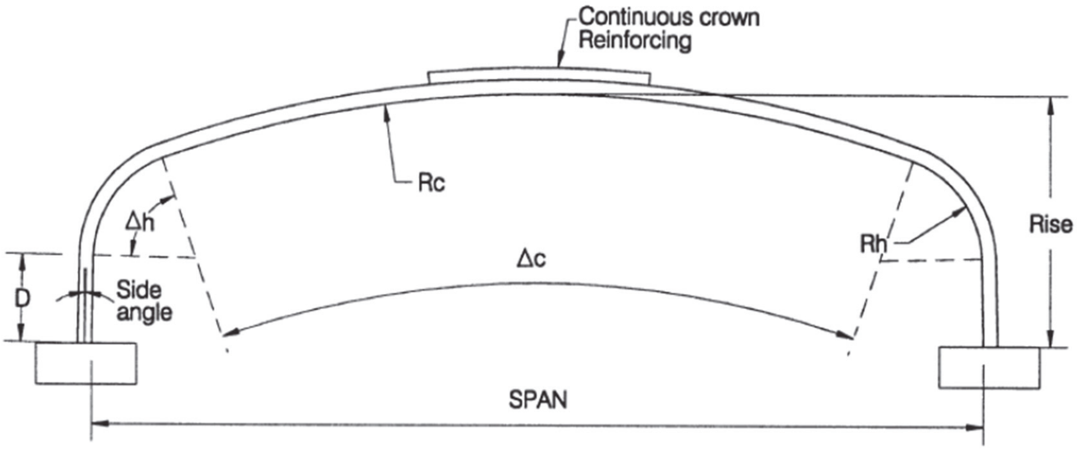


Figure 4.1. Cross-sectional view of the culvert.

Table 4.1. Geometry of the three culverts

Culvert span, S	7 m	14 m	28 m
Rise	2200	3476	4800
Crown radius, R_c	8820	16430	40000
Crown angle, Δ_c	53	46	38
Haunch radius, R_h	1016	1454	1654
Haunch angle, Δ_h	69.69	68	68
Side angle, D	825	1000	1100

4.3.2 Meshing and boundary conditions

The first two modes in Plaxis 2D are the soil and structure mode, which defines the geometry of the model. The two-dimensional geometry of the models used, and the compacted layers are shown schematically in Figure 4.2 and 4.3, respectively. A ‘very fine’ global coarseness value was utilized to generate the mesh for each model, with emphasis placed on refining the mesh of the metal plates in order to accurately depict deformation.

For the FE model, 15 node triangular elements were selected to stimulate the soil layers and the culvert as it generates a very high-quality stress result. Figure 4.4 illustrates a typical two-dimensional FE model displaying element contours. The plate that represents the culvert is divided into smaller plates to mimic its actual shape. The friction behaviour at the culvert-soil interface and the interaction between the concrete footings and soil layers were stimulated using five node interface elements from the Plaxis library and a strength reduction factor, R_{inter} of 0.67 was used to model the roughness of the interaction. In the model, fully fixed boundary conditions were constructed at the base for static analyses, while the lateral boundaries were set as free in the vertical direction and fixed in the horizontal direction. The extend of the overall model boundaries varied as a function of the trench width, side slope, and soil cover depth.

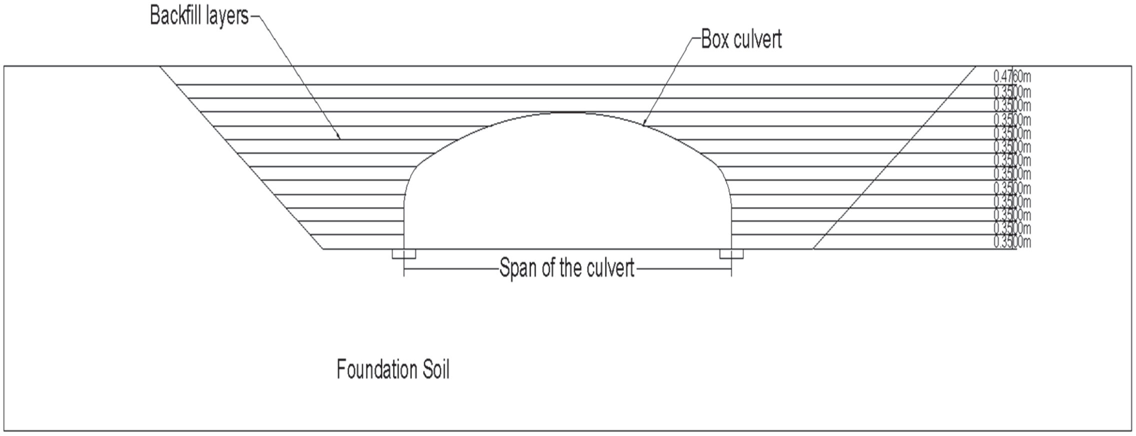


Figure 4.2. Vertical cross-section schematic of 2D model geometry

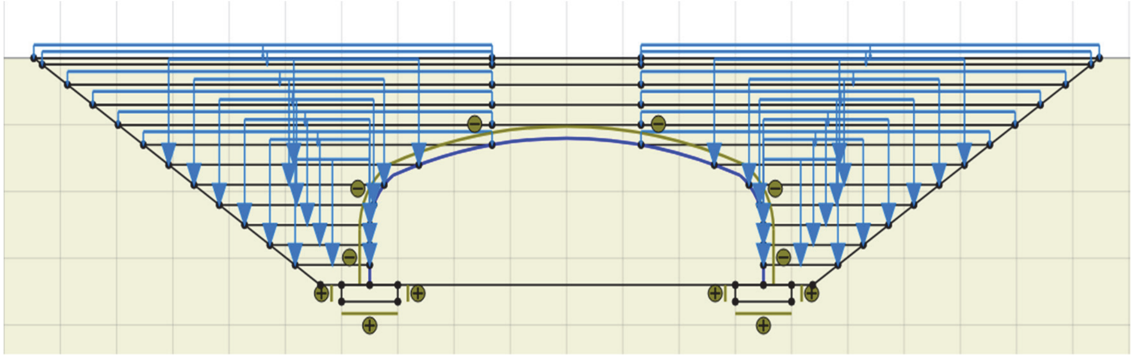


Figure 4.3. Two-dimensional model with compacted layers

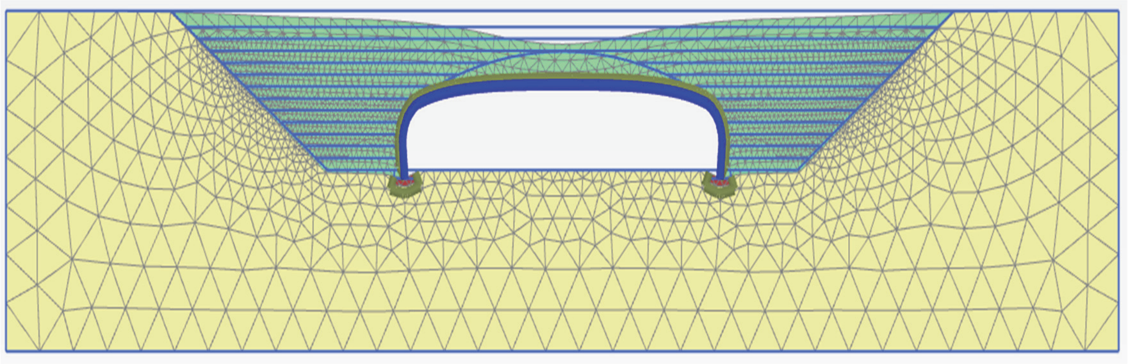


Figure 4.4. Two-dimensional finite element mesh used in the parametric study

4.3.3 Material properties

4.3.3.1 Backfill and Subgrade Properties

The foundation soil and the backfill were modelled using 15-noded triangular elements. The used backfill soil was compacted in layers, 350 mm thickness. The Hardening Soil with a small strain model was used to model the soil behaviour, which stimulates the soil stress-strain behaviour of non-linear and stress-dependent soils. The soil parameters of the backfill and foundation soil considered in the study are shown in table 4.2. Some of the soil properties such as unit weight, stiffnesses, and interface strength reduction factor were varied as part of the parametric study, while keeping other soil parameters constant. Soil's oedometer modulus E_{oed}^{ref} and unload-reload modulus E_{ur}^{ref} were adjusted in proportion to the secant modulus E_{50}^{ref}, maintaining a constant correlation between the three stiffness moduli (where E_{oed}^{ref}=0.8, E_{50}^{ref}, and Eur ref = 3.0 E_{50}^{ref}). The stiffness values stated for the HS model are founded on a 100kPa reference pressure.

Table 4.2. soil parameters of the backfill and foundation soil.

Soil Parameter	Symbols	Units	Backfill soil	Foundation soil
Dry unit weight	γ_{dry}	kN/m3	19.5	18
Saturated unit weight	γ_{sat}	kN/m3	22	21
Secant stiffness in standard drained triaxial test	E_{50}^{ref}	kPa	60	40
Tangent stiffness for primary oedometer loading	E_{oed}^{ref}	kPa	48	40
Unloading/reloading stiffness	E_{ur}^{ref}	kPa	180	120
Cohesion	c′	kPa	2	2
Internal friction angle	φ′	Deg.	40	40
Dilatancy	ψ	Deg.	10	10
Power for stress-level dependency of stiffness	m		0.5	0.5

4.3.3.2 Corrugated steel properties

The corrugated box culvert was modeled as an elastic material using the Plaxis 2D plate element, which can display both isotropic and orthotropic behaviour, while also employing axial and flexural rigidities. A deep corrugated structural plate, as illustrated in Figure 4.5, has a wavelength of 381 mm, corrugation depth of 140 mm, and plate thickness of 7 mm. The properties in Table 4.3 represent the area, moment of inertia, section modulus, and radius of gyration of the corrugated steel plate. Corrugated steel box culverts attain a low and wide rectangular shape by means of including specialized rib plates (if necessary) to the conventional deep corrugated plate sheets. The resultant joint section enhances the flexible capacity that is essential for achieving the extremely flat top and pointed edges.

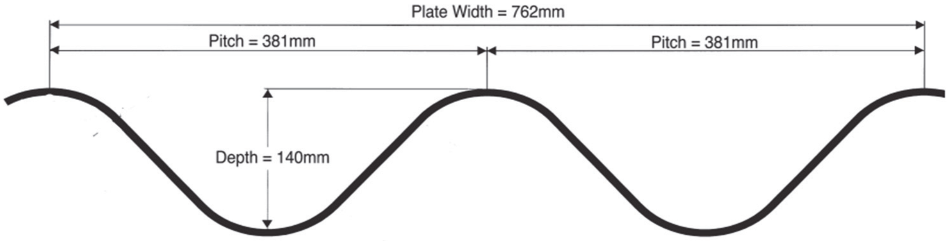


Figure 4.5. The corrugation profile and its geometrical characteristics

Table 4.3. Properties of Corrugated Steel Plate

Properties	**Units**	**Corrugated Steel plate**
Plate thickness, t	mm	7
Elasticity Modulus, E_{st}	Gpa	205.7
Cross sectional area, A	mm^2/mm	9.8
Cold formed yield strength, f_{yk}	MPa	352
Moment of Inertia, I_{st}	mm^4/mm	22,856
Section modulus, W	mm^3/mm	296

4.3.4 FE construction sequence

The construction sequence stages for the calibrated FE model were stimulated in the Plaxis 2D software. The initial stage was performed by the K0 technique, where initial geostatic in-situ stresses were established. The groundwater table was considered to be located beneath the culvert profile. In the first phase, the foundation soil, culvert plates, foundation, and soil-culvert interface were all activated, and all displacements were reset to zero. The layers are sequentially activated with their corresponding surface load, which is then deactivated in the following stage, and the next layer and its load are subsequently activated, continuing until the compaction process is finished. Figures 4.6 and 4.7 illustrate the finite element mesh with compacted layers and the simulation of the compaction process.

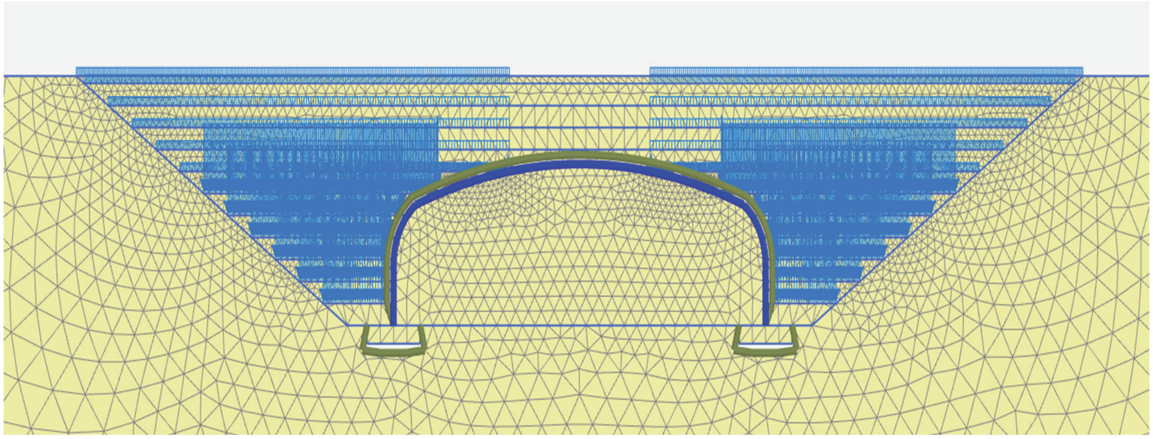


Figure 4.6. Finite element mesh with compacted layers.

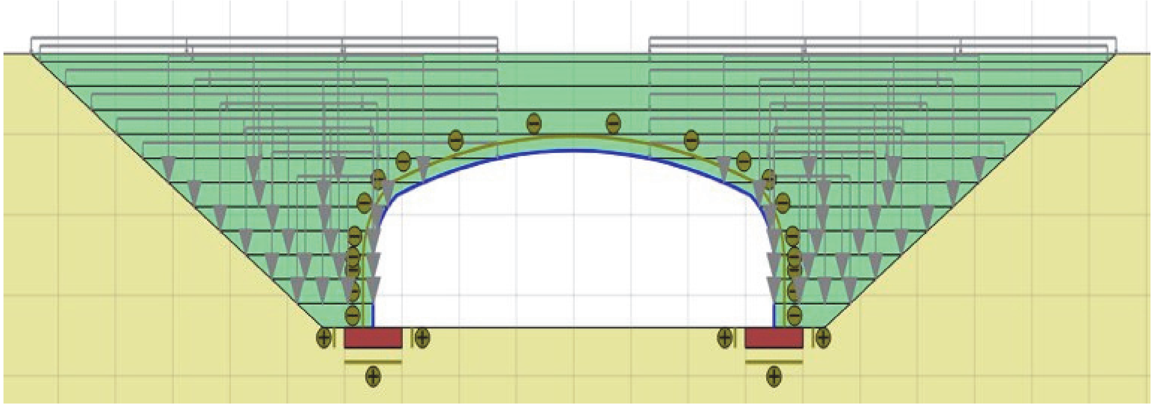


Figure 4.7. the simulation of the compaction process.

4.4 Study Parameters

The following four parameters were varied to evaluate their influence on the crown deformations, bending moments, and thrusts in the box culvert during backfilling.

- Trench width
- Trench side slope
- Soil cover depth
- Backfill soil stiffness

A series of 2D FE models were analyzed using three different culvert sizes: small span, medium span and large span culverts of 7 m, 14 m, and 28 m, respectively. Twelve sets of models (fifty-seven simulations) in total were carried out as part of the study. Figure 4.8 and Table 4.4 illustrate the parametric study and work plan parameters that were investigated in this research. The parametric study consisted of developing a series of 2D FEM simulations. In each simulation, a single parameter was changed; while keeping the other parameters constant. The first parametric study investigated the effects of changing trench widths (B), values from B = 0.125S, 0.25 S, 0.5S, 0.75S, 1.00S, where S is the span of the culvert. For this set of models, trench side slope, backfill soil stiffness, and soil cover depth were kept constant. The second parametric study focuses mainly on the effect of varying trench side slopes on the performance of the culvert. For a fixed cover depth of t = 1.2 m, slopes with different values of 1: n are considered, where n = 0.75, 1, 1.25, 1.5, 2. The effect of changing the soil cover depth (ie. The backfill height) above the culvert crown was investigated in the third parametric study. Soil cover depths of 0.1S, 0.2S, 0.4S, 0.8S, 1.0S were considered. The culvert simulated in this set had a constant trench geometry and backfill stiffness. The fourth parametric study investigated the effect of using backfill soil with varying stiffness, ranging from loose sand to gravel. Four types of backfill soil utilized in this study were loose sand, medium sand, dense sand, and very dense sand. Elastic modulus was determined by subjecting them to a confining pressure of 100 kPa.

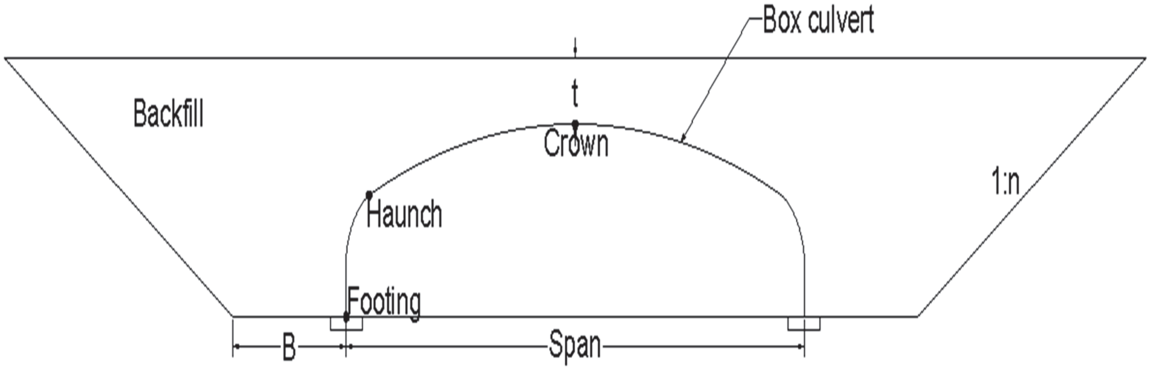


Figure 4.8. Variable parameters in the parametric study

Table 4.4. the parametric study and work plan parameters

Set	**Span length**	**Trench width**	**Trench Side Slope 1: n➔ V:H,**	**Soil cover depth**	**Backfill Soil Stiffness**
Set 1	7m	B = 0.125S, 0.25S, 0.5S, 0.75S, 1.00S	n = 1.5	t=1.2 m	Dense soil
Set 2	7m	B= 0.25S	n=0.75, 1, 1.25, 1.5, 2	t=1.2 m	Dense soil
Set 3	7m	B= 0.25S	n = 1.5	t =0.1S, 0.2S, 0.4S, 0.8S, 1.0S	Dense soil
Set 4	7m	B= 0.25S	n = 1.5	t=1.2 m	Loose, Medium, Dense, Very Dense
Set 5	14m	B = 0.125S, 0.25S, 0.5S, 0.75S, 1.00S	n = 1.5	t=1.2 m	Dense soil
Set 6	14m	B= 0.25S	n=0.75, 1, 1.25, 1.5, 2	t=1.2 m	Dense soil
Set 7	14m	B= 0.25S	n = 1.5	t =0.1S, 0.2S, 0.4S, 0.8S, 1.0S	Dense soil
Set 8	14m	B= 0.25S	n = 1.5	t=1.2 m	Loose, Medium, Dense, Very Dense
Set 9	28m	B = 0.125S, 0.25S, 0.5S, 0.75S, 1.00S	n = 1.5	t=1.2 m	Dense soil
Set 10	28m	B= 0.25S	n=0.75, 1, 1.25, 1.5, 2	t=1.2 m	Dense soil
Set 11	28m	B= 0.25S	n = 1.5	t =0.1S, 0.2S, 0.4S, 0.8S, 1.0S	Dense soil
Set 12	28m	B= 0.25S	n = 1.5	t=1.2 m	Loose, Medium, Dense, Very Dense

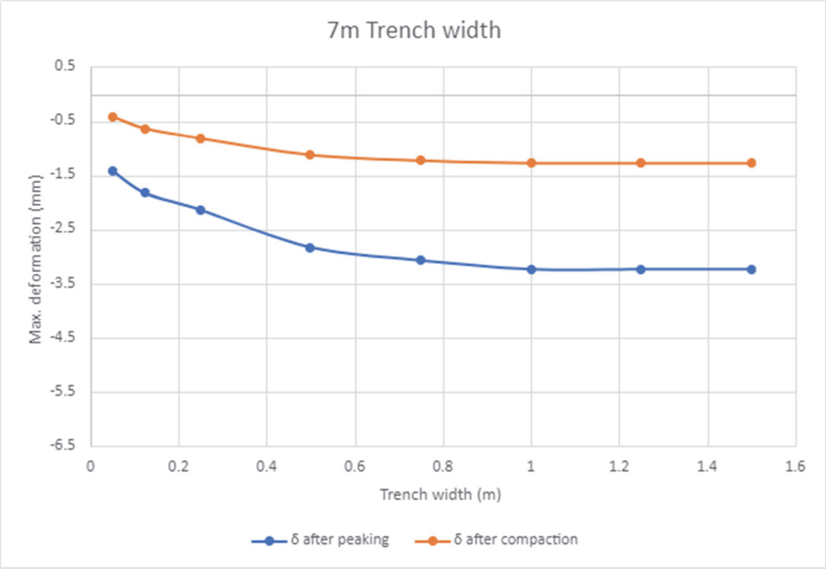
4.5 Results and Discussions

This part of the section presents findings of the parametric studies, which used the FE models to investigate the effects of varying the trench width, trench side slope, soil cover depth, and backfill soil stiffness on Corrugated box culvert's crown deformation, bending moments, and thrust forces.

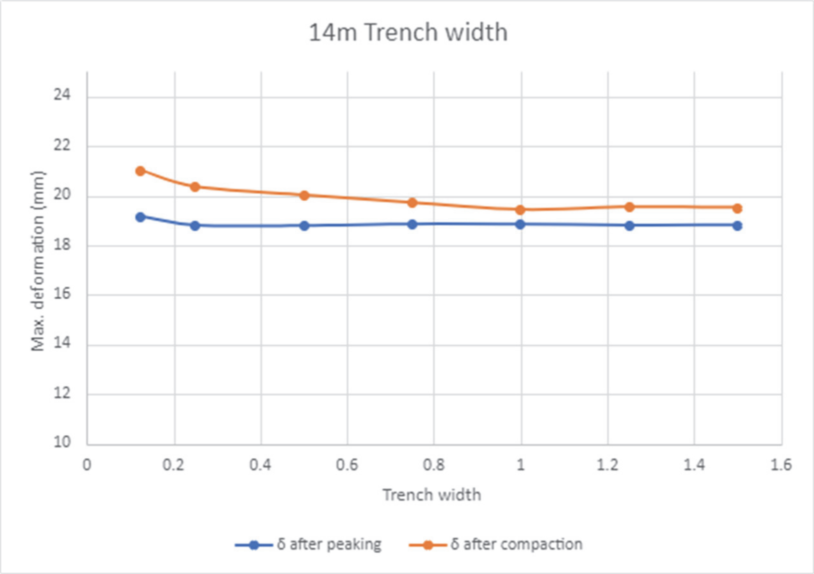
4.5.1. Effect of Trench width

Trench width allows better compaction of the soil around the culvert, which increases the lateral support of the culvert and improves its ability to withstand heavy loads or external forces. The width of the trench depends on the culvert geometry and the backfilling process. To investigate the effect of trench width B, a numerical analysis was performed for different values of B = 0.125S, 0.25S, 0.5S, 0.75S, and 1.00S, where S is the span of the culvert. This section explains the effect of trench width on the vertical deformation at crown, the thrusts, and bending moments for small span (7m), medium span (14m), and large span (28m) culverts, respectively.

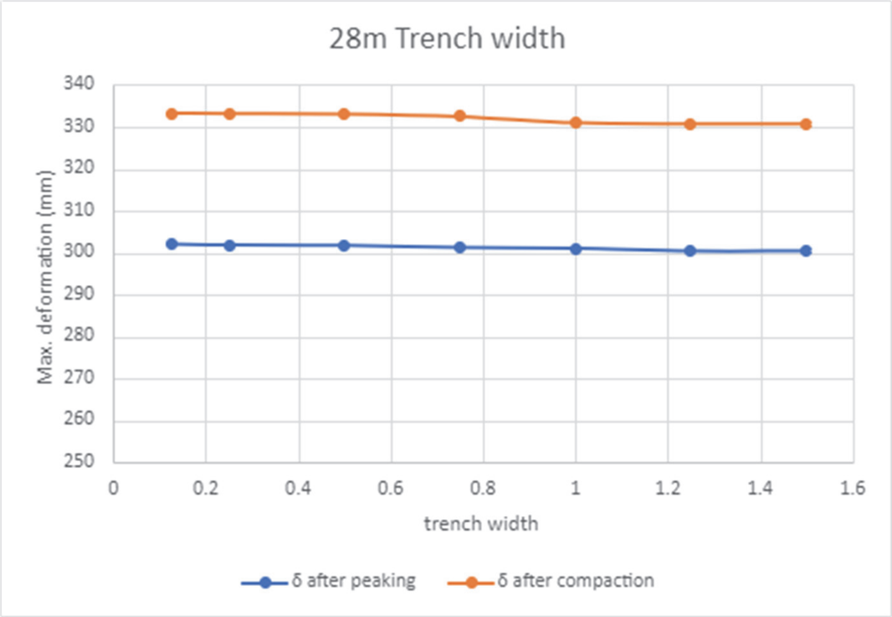
Figure 4.9 compares variations in crown deformation after peaking and compaction with increasing trench width for three different culvert spans. It can be seen that for different culvert spans, the crown deformation gradually decreases as the trench width becomes equal to half the length of the span and then the deformation remains constant with the increase in the trench width. Figures 4.10 and 4.11 compare the variations in bending moment and thrust at three different locations (crown, haunch, and footing) for three different culvert spans. The bending moment and thrusts for three different spans of the culvert (7m, 14m, and 28m) remain unchanged with different values of trench width, B. In general, the trench width for a corrugated box culvert has no significant effect on the results. As the loads act on confined areas surrounding the culvert area, increasing the trench width will have less effect on the structure.



a) Crown deformation after peaking and compaction v/s trench width for 7m span culvert

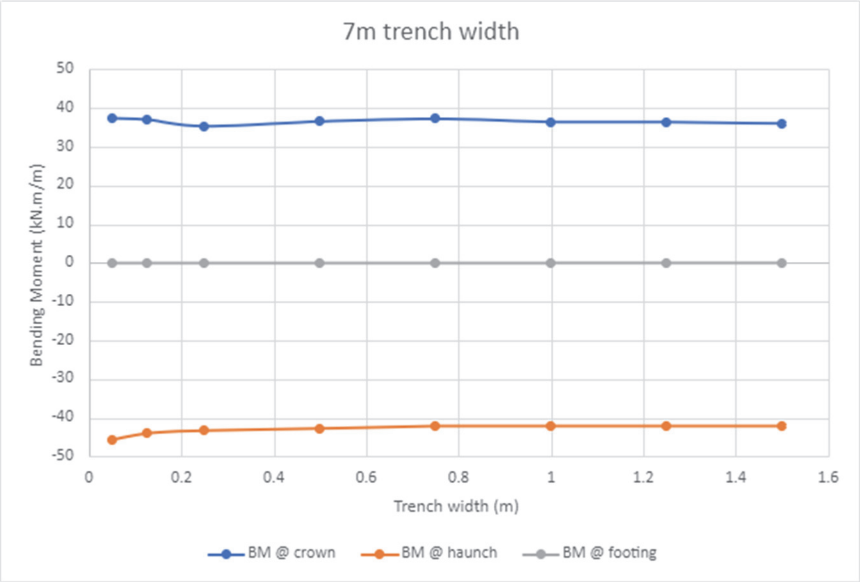


b) Crown Deformation after peaking and compaction v/s trench width for 14m span culvert

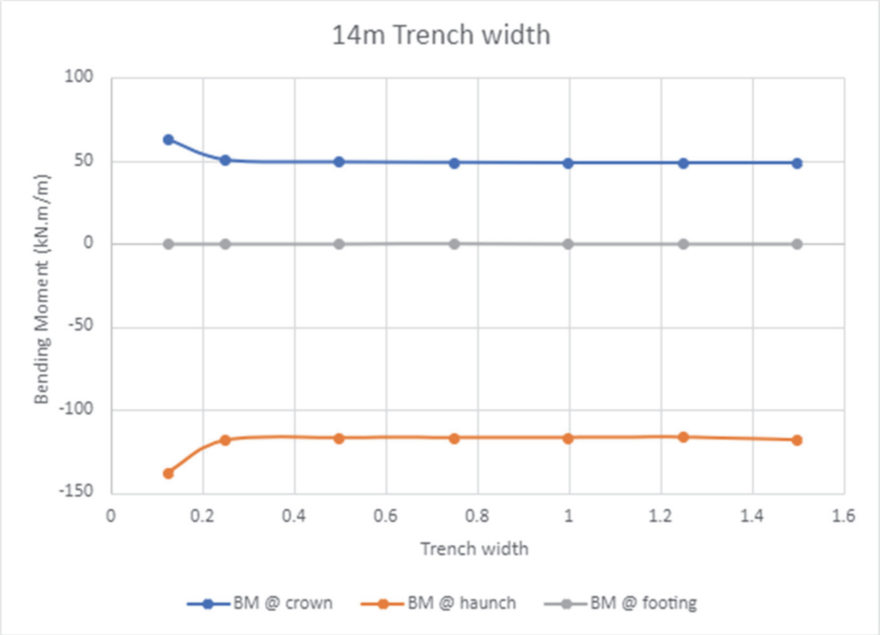


c) Crown deformation after peaking and compaction v/s trench width for 28m span culvert

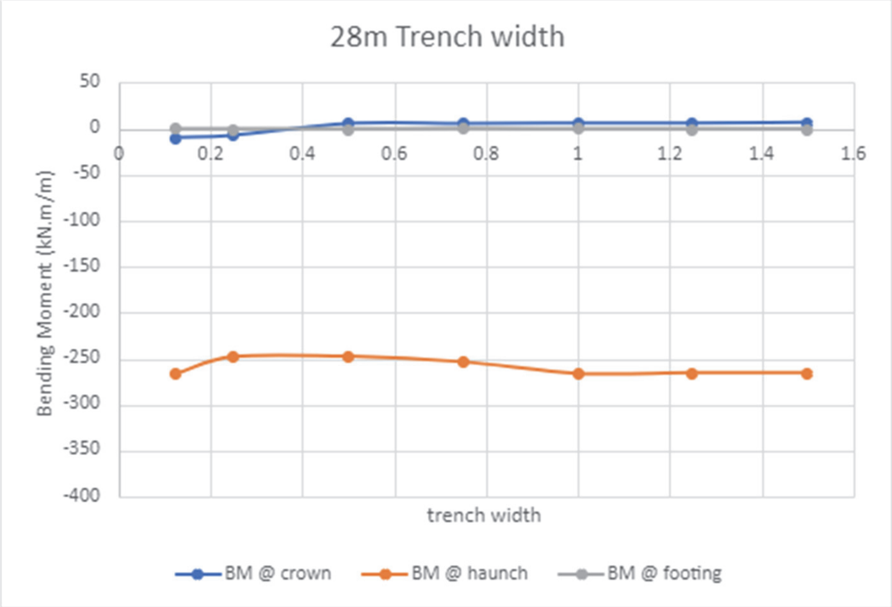
Figure 4.9. Effect of trench width on the crown deformation (after peaking and compaction) for different spans of culvert.



a) Bending moment v/s trench width for 7m span culvert

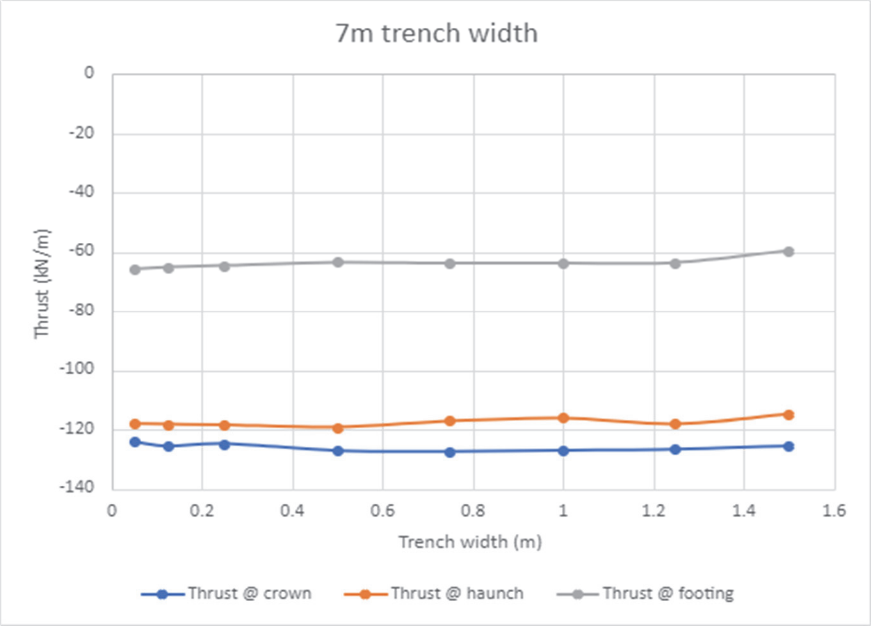


b) Bending Moment v/s trench width for 14m span culvert

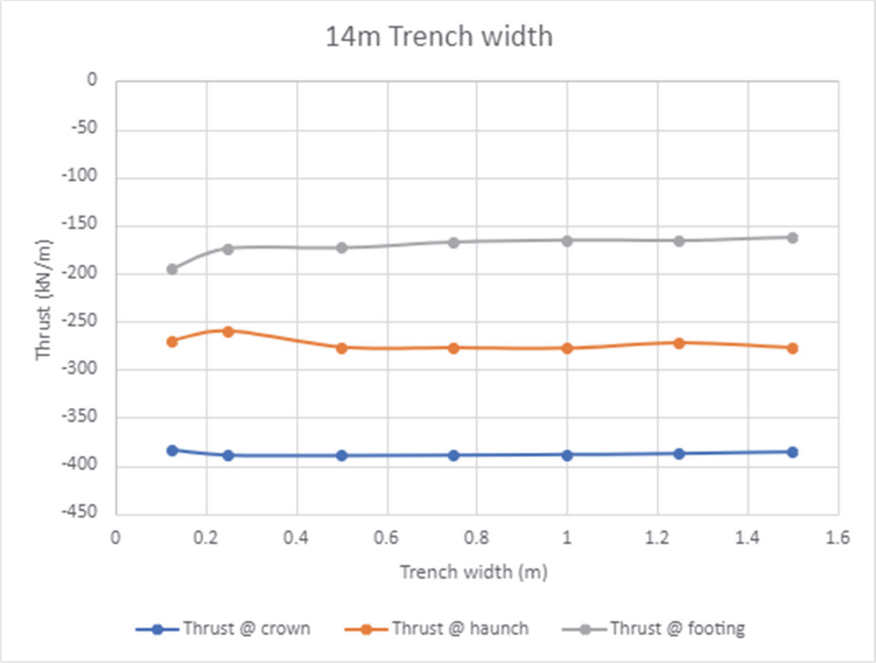


c) Bending Moment v/s trench width for 28m span culvert

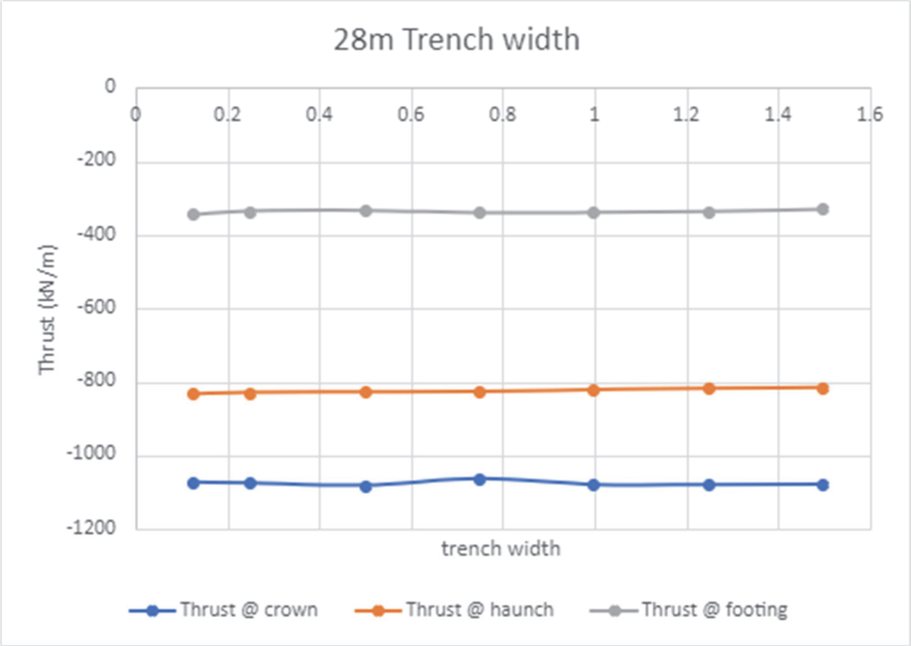
Figure 4.10. Effect of trench width on the bending moment for different spans of culvert.



a) Thrust v/s trench width for 7m span culvert.



b) Thrust v/s trench width for 14m span culvert.



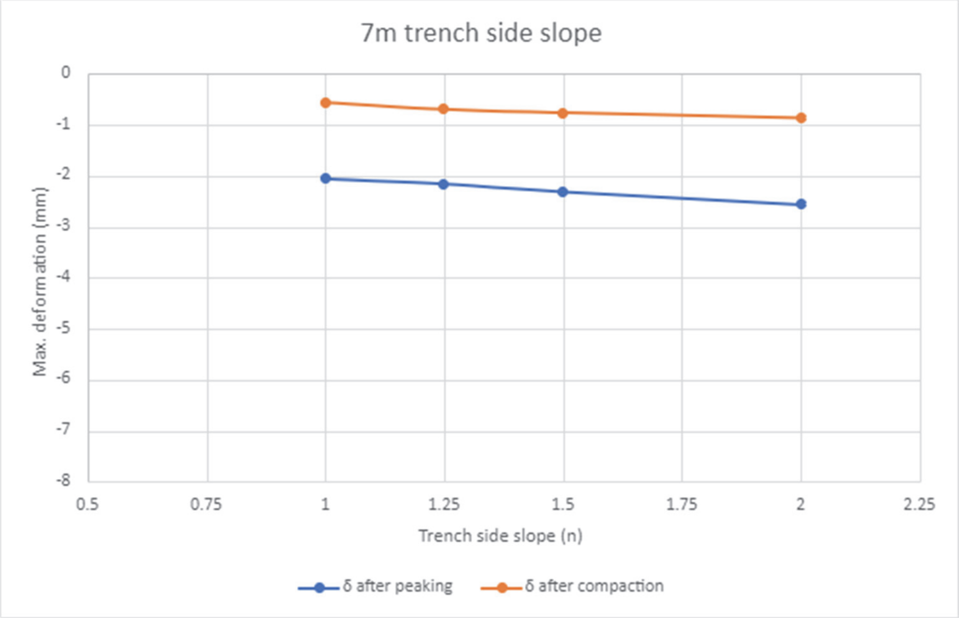
c) Thrust v/s trench width for 28m span culvert.

Figure 4.11. Effect of trench width on the thrusts for 28m.

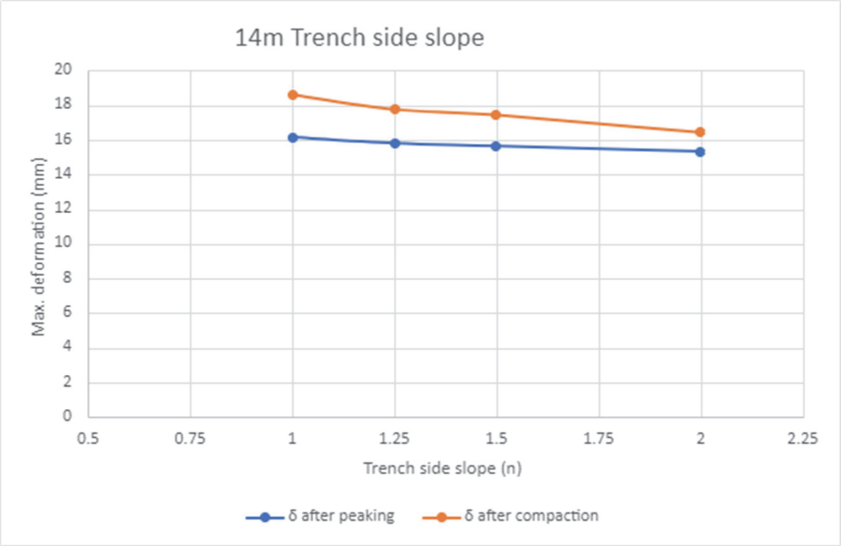
4.5.2 Effect of Trench side slope

The trench side slope should be designed to minimize lateral pressure and settling while ensuring sufficient clearance for the culvert. When constructing culverts, it is important to have sloping trench sides that aid in the excavation process as well as the compaction of the backfill soil. However, it is essential to consider the stability of the side slopes during construction by taking into account the characteristics of the existing soil. For a fixed trench width of B = 0.25 S and cover depth of 1.2 m, slopes with different values of 1: n are considered in this parametric study, where n = 1, 1.25, 1.5, 2. The following section explains the effect of different trench side slopes on the crown deformation (after peaking and compaction at the crown level), bending moments, and thrusts for small span (7m), medium span (14m), and large span (28m) culverts, respectively.

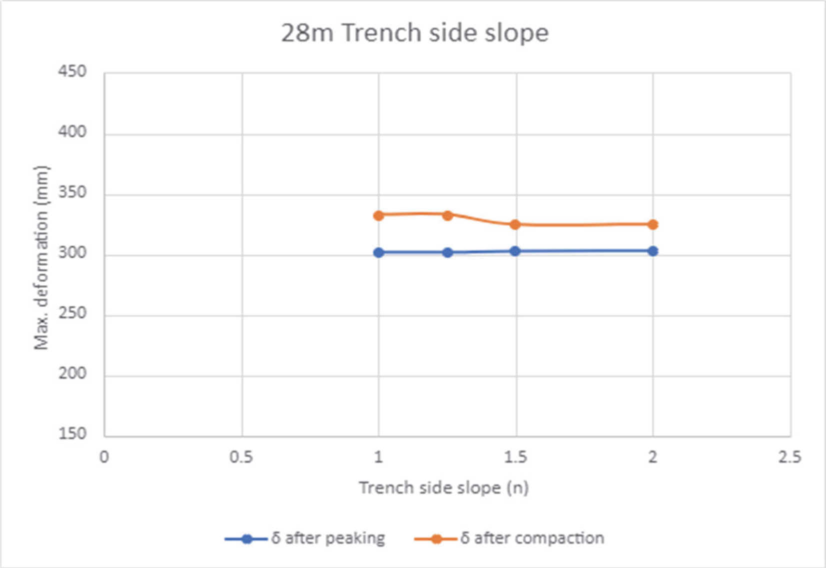
Figure 4.12 compares the variation in crown deformation after peaking and compaction with increasing the trench side slope for three different span culverts. A slight decrease in crown deformation from -0.56 mm, 18.6mm, 332.974mm at n=1 to -0.86mm, 16.431mm, and 324.915mm at n=2 for 7m, 14m, and 28m span culverts, respectively. Figures 4.13 and 4.14 compare the variations in bending moment and thrust at three different locations (crown, haunch, and footing) for three different culvert spans. The crown deformation is almost the same for different side slopes as it usually depends on the topsoil cover rather than the side boundary effect. The effect of the side slope on the culverts internal forces can be considered negligible, as the thrust and bending moments at crown, haunch, and footings are almost the same for four different trench side slopes.



a) Crown deformation after peaking and compaction v/s trench side slope for 7m span culvert.

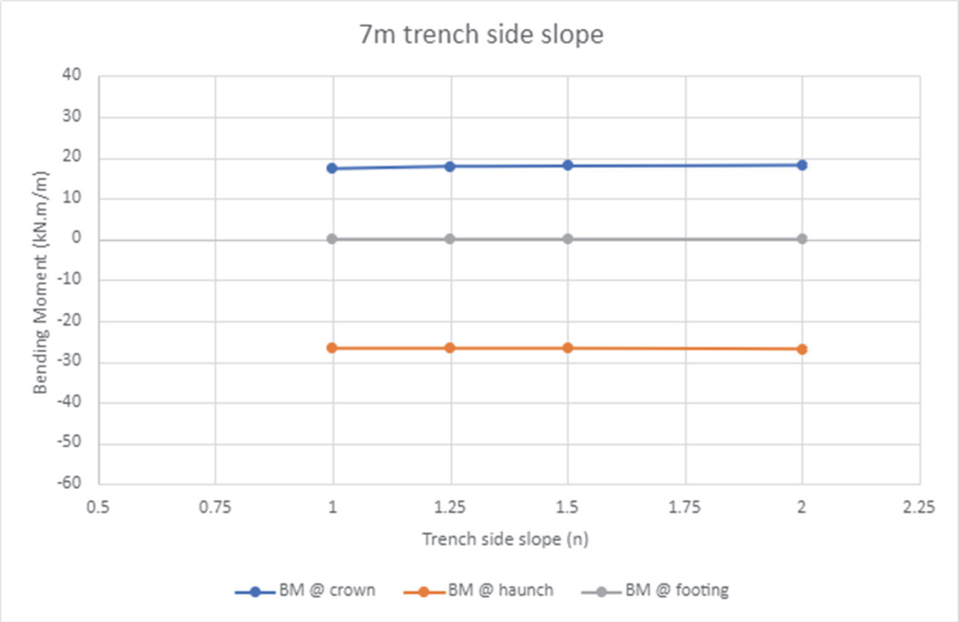


b) Crown deformation after peaking and compaction v/s trench side slope for 14 m span culvert

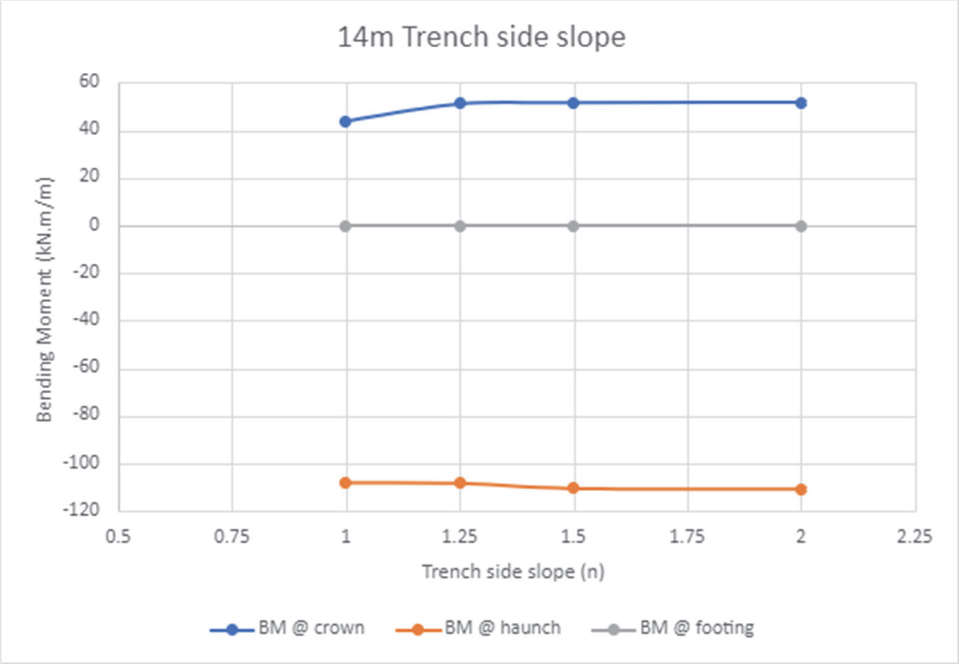


c) Crown deformation after peaking and compaction v/s trench side slope for 28 m span culvert

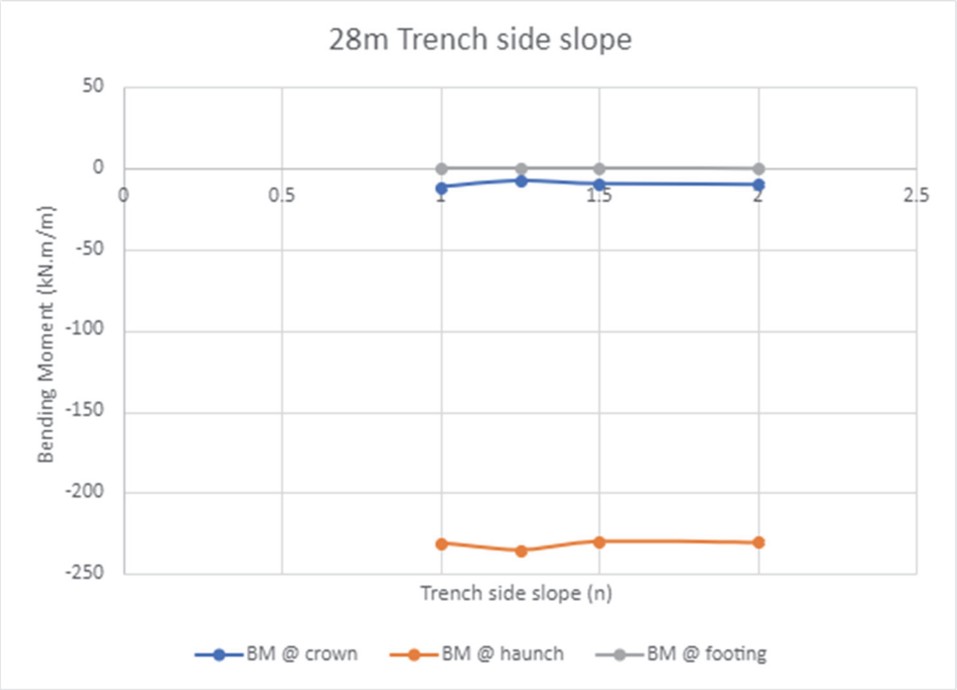
Figure 4.12. Effect of trench side slope on the crown deformation (after peaking and compaction) for different spans of culvert.



a) Bending moment v/s trench side slope for 7m span culvert

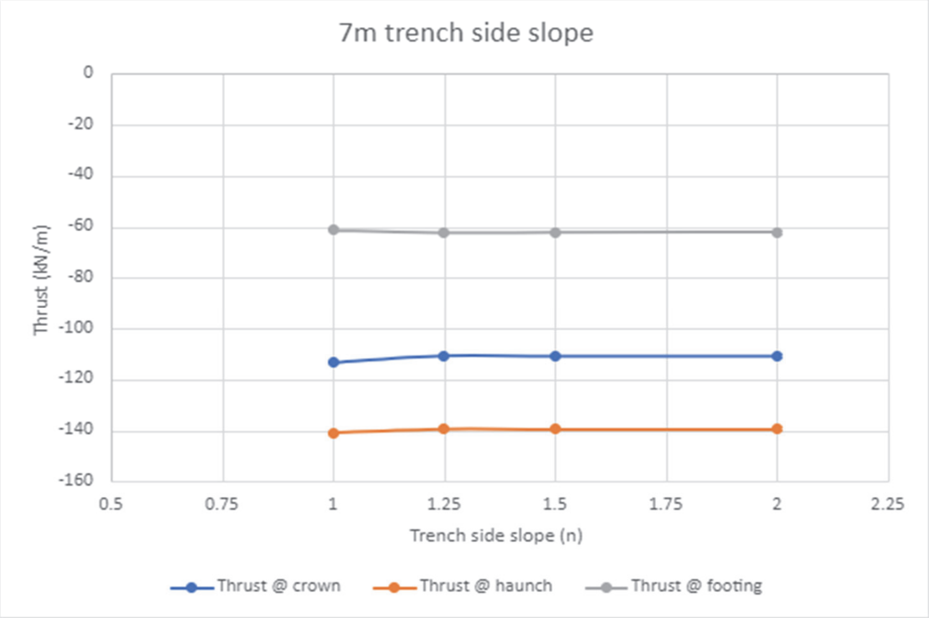


b) Bending moment v/s trench side slope for14 m span culvert

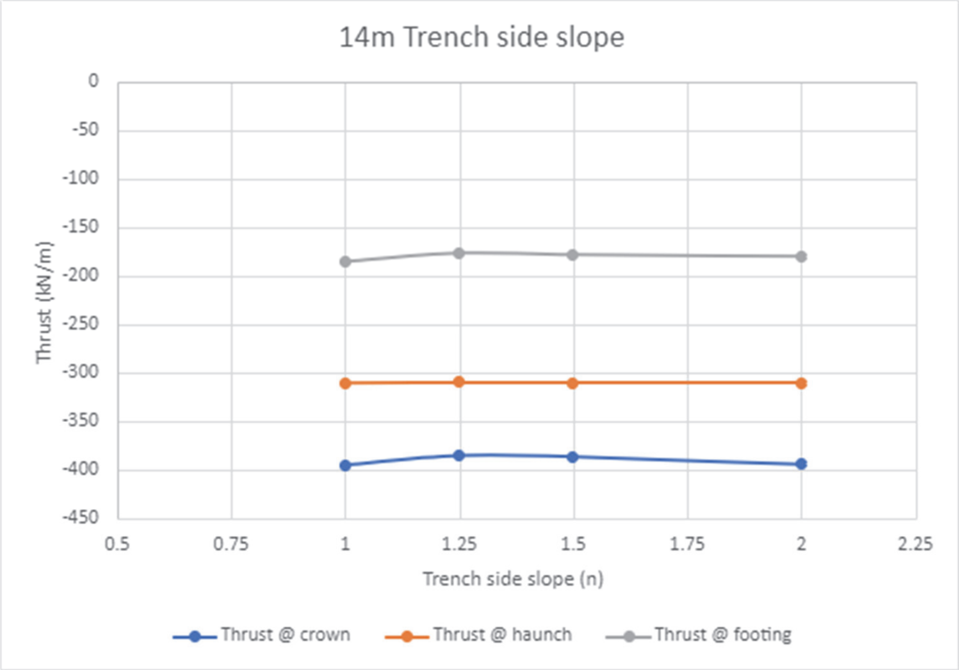


c) Bending moment v/s trench side slope for 28 m span culvert

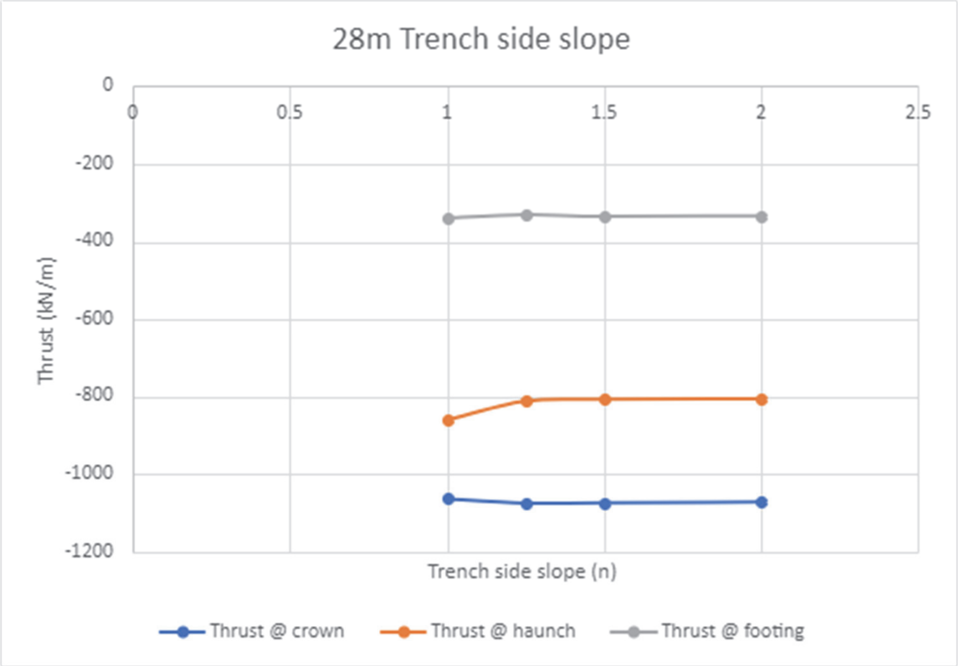
Figure 4.13. Effect of trench side slope on the bending moments for different spans of culvert.



a) Thrust v/s trench side slope for 7m span culvert



b) Thrust v/s trench side slope for 14m span culvert



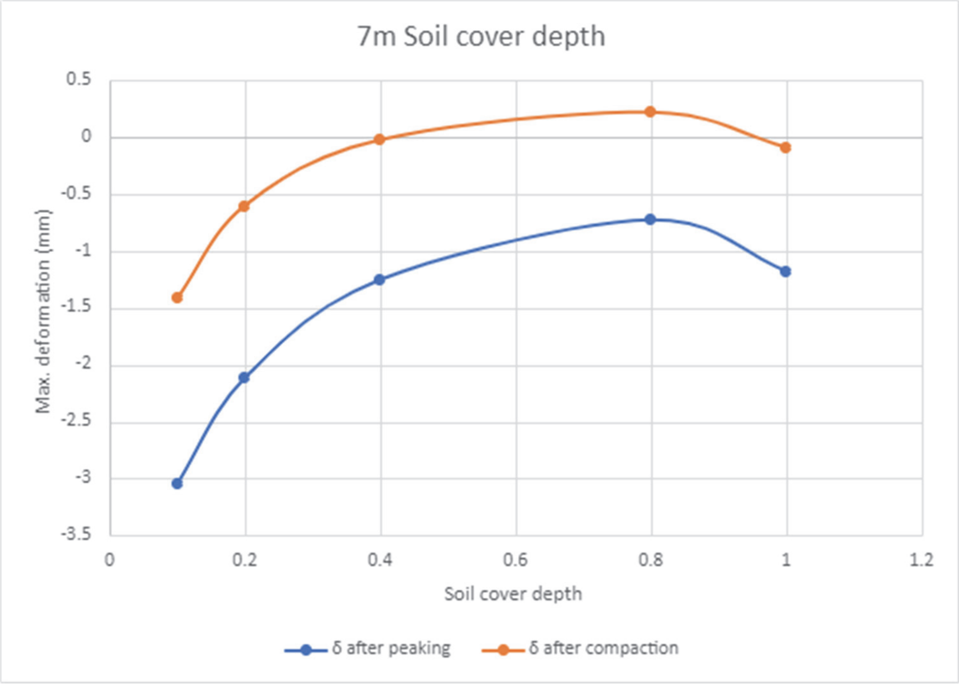
c) Thrust v/s trench side slope for 28 m span culvert

Figure 4.14. Effect of trench side slope on the thrusts for different spans of culvert.

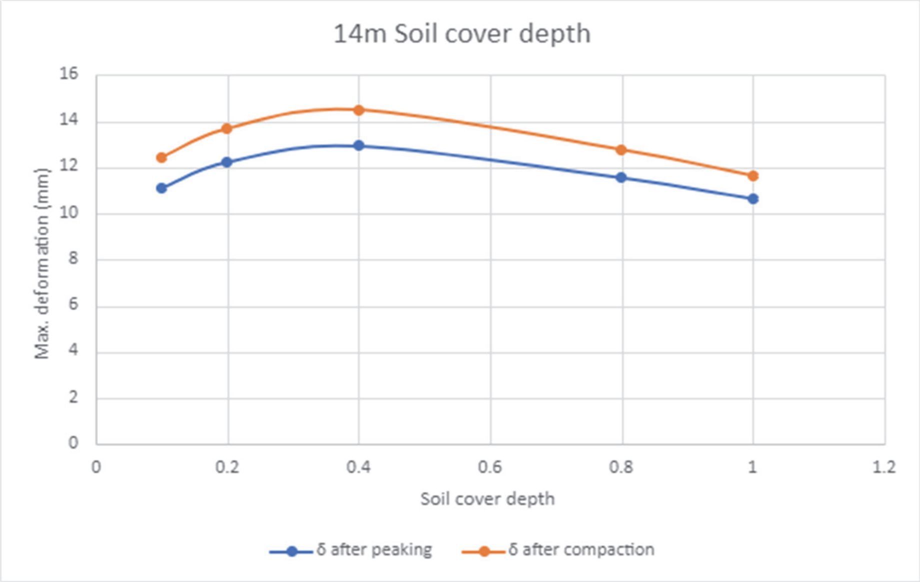
4.5.3 Effect of the Soil Cover Depth

The soil cover depth above the culvert has a significant impact on the performance and longevity of the culvert. It ensures the load-bearing capacity, protection against water infiltration and frost heave, and accessibility for maintenance and repair work. The layers above the culvert (especially near the crown) need to be compacted very carefully and hence decrease the settlement caused by traffic loads. In this analysis, soil cover depths (t) of 0.1S, 0.2S, 0.4S, 0.8S, and 1.0S, where S is the span of the culvert were considered for this study. The backfill soil stiffness and trench geometry are kept constant to investigate the effect of soil cover depth. This section clarifies how the crown deformation, bending moments, and thrusts for culverts with small (7m), medium (14m), and large (28m) spans are influenced by various soil cover depths.

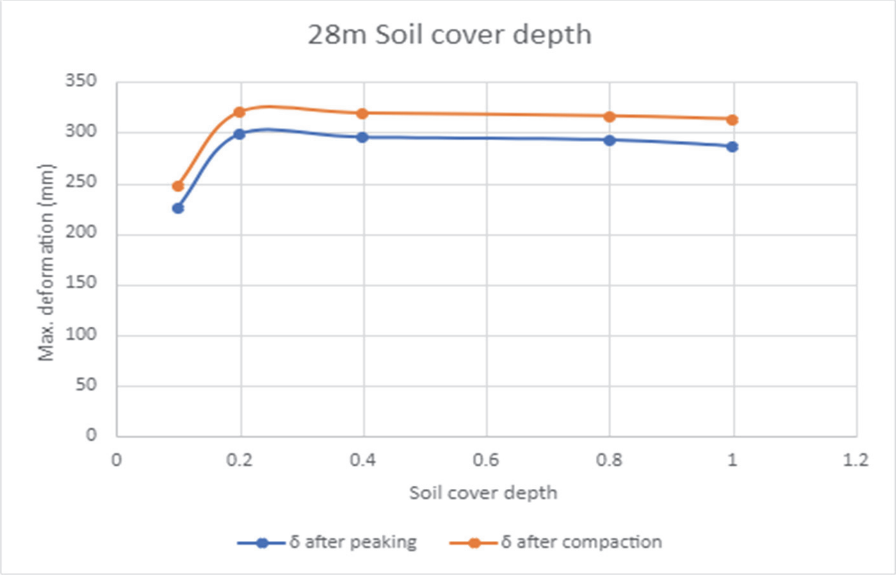
Figure 4.15 compares variations in crown deformation after peaking and compaction with increasing soil cover depth for three different culvert spans. It can be seen that for all three spans of culvert, the maximum crown deformation is achieved at a height of 5.6m. The crown deformation gradually increases and after 5.6 m, it gradually decreases as the height of the soil cover increases. This is due to the additional weight of the soil cover, which is then transferred to the sides, leading to a small portion of the loads on the crown region. Figures 4.16 and 4.17 compare the variations in bending moment and thrust at three different locations (crown, haunch, and footing) for three different culvert spans. It can be seen from the graph that there is a nonlinear relationship between the maximum bending moment and the cover depth, while the maximum thrust forces at the culvert base increase directly with the soil cover depth. The bending moment at the footing remains the same for the culverts while thrust at the footing increases with the soil cover depth. The height of the soil cover had the greatest influence on the thrust of the culvert. The thrust at haunch and crown is greater than the thrust at footing as the soil cover depth is increased. This is due to the additional volume of soil above the culvert.



a) Crown deformation after peaking and compaction v/s soil cover depth for 7m span culvert.

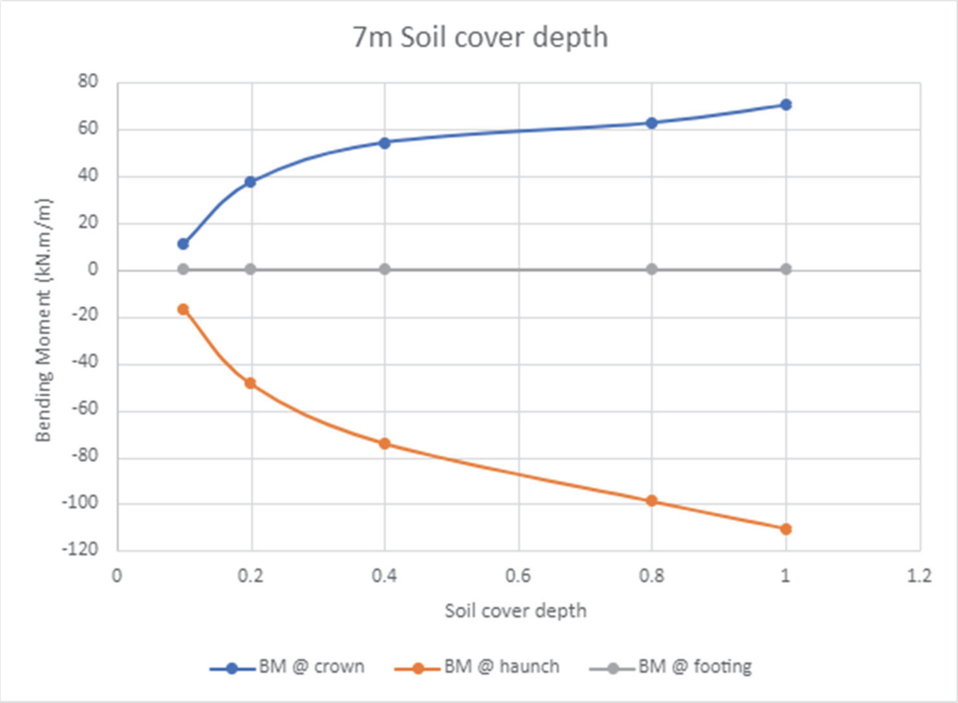


b) Crown deformation after peaking and compaction v/s soil cover depth for 14 m span culvert.

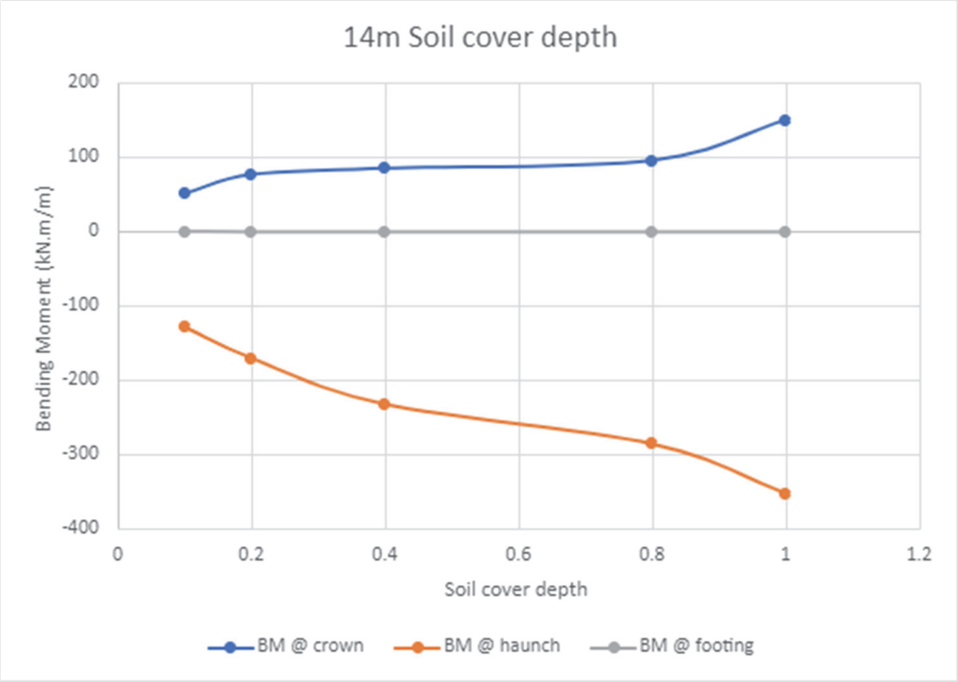


c) Crown deformation after peaking and compaction v/s soil cover depth for 14 m span culvert.

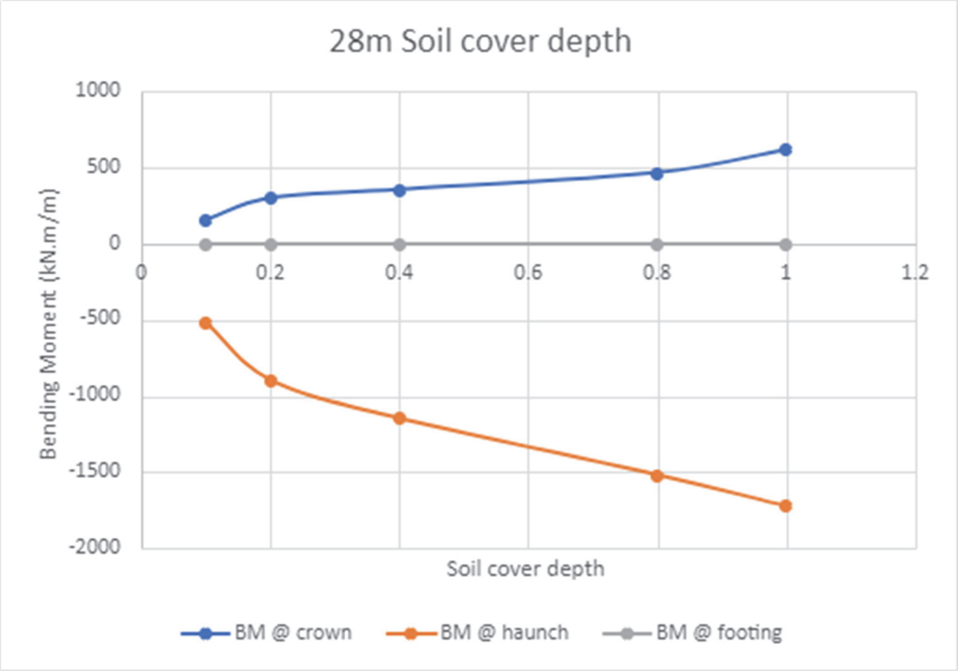
Figure 4.15. Effect of soil cover depth on the crown deformation (after peaking and compaction) for different spans of culvert.



a) Bending Moment v/s soil cover depth for 7m span culvert.

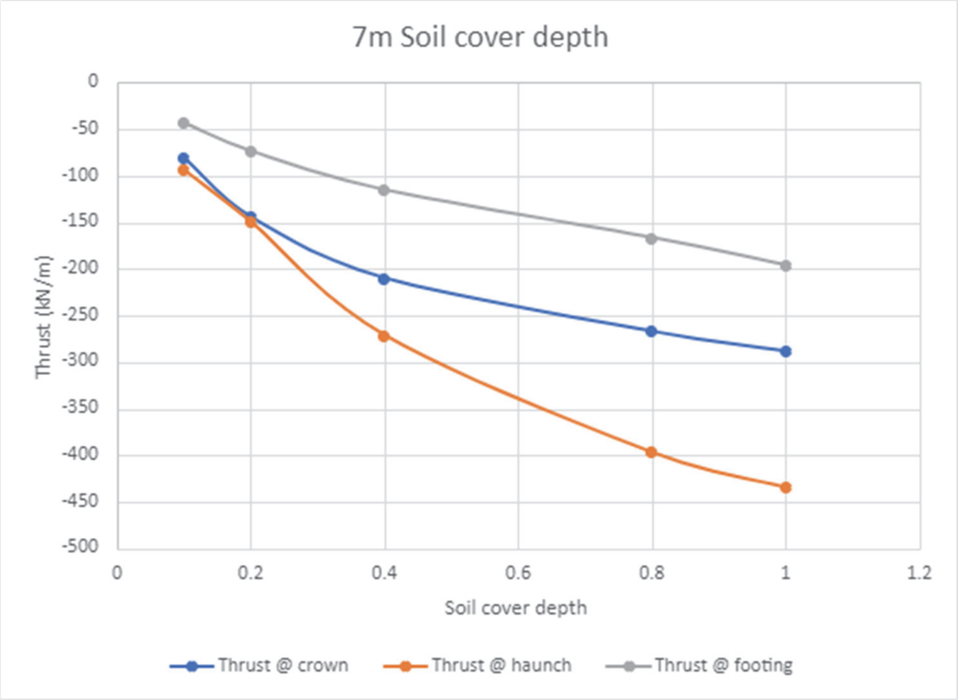


b) Bending Moment v/s soil cover depth for 14 m span culvert.

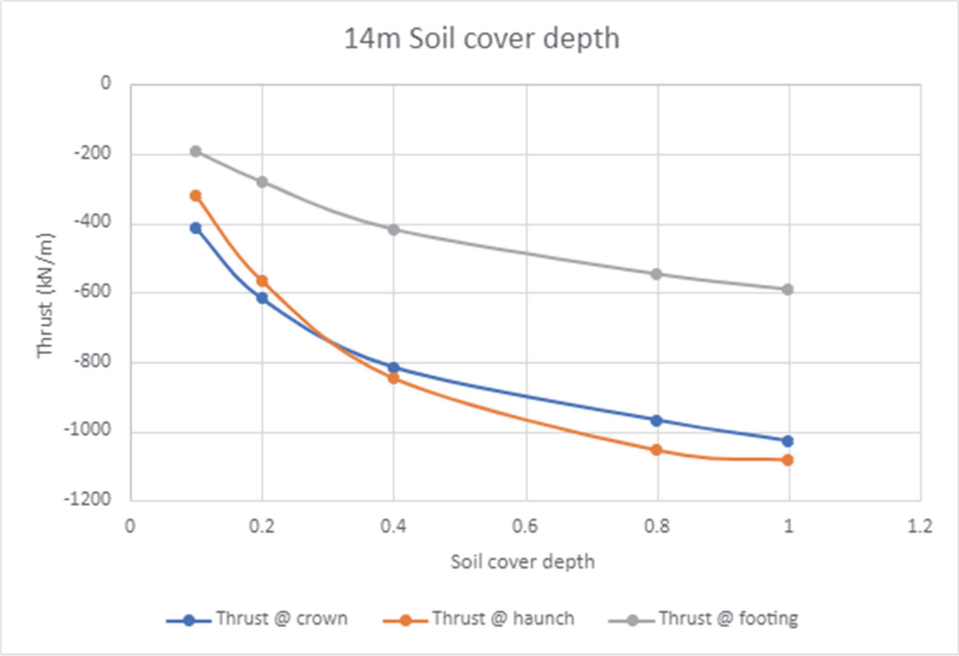


c) Bending Moment v/s soil cover depth for 28 m span culvert.

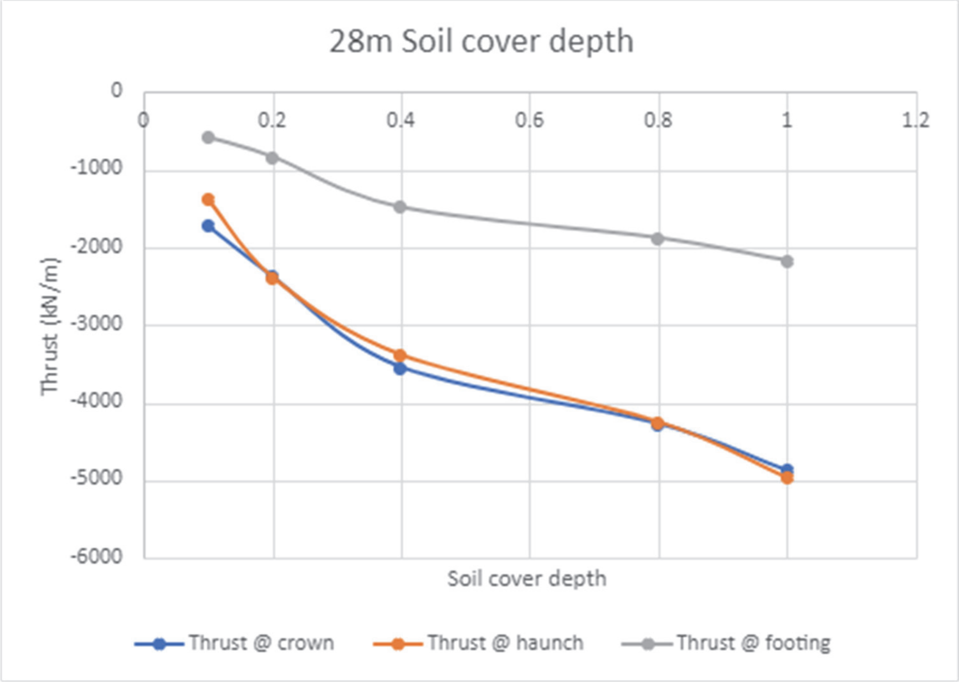
Figure 4.16. Effect of soil cover depth on the bending moment for different spans of culvert.



a) Thrust v/s soil cover depth for 7m span culvert.



b) Thrust v/s soil cover depth for 14 m span culvert.



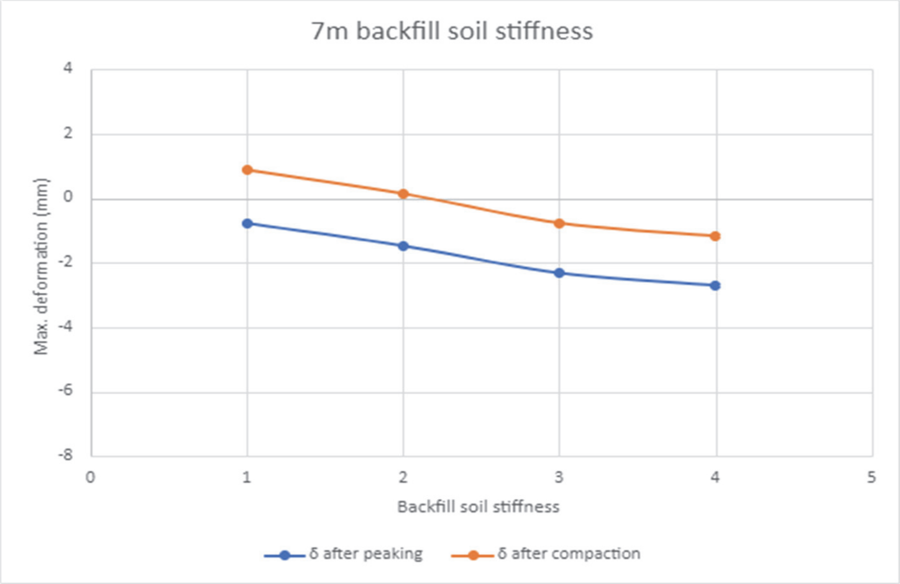
c) Thrust v/s soil cover depth for 28 m span culvert.

Figure 4.17. Effect of soil cover depth on the thrusts for different spans of culvert.

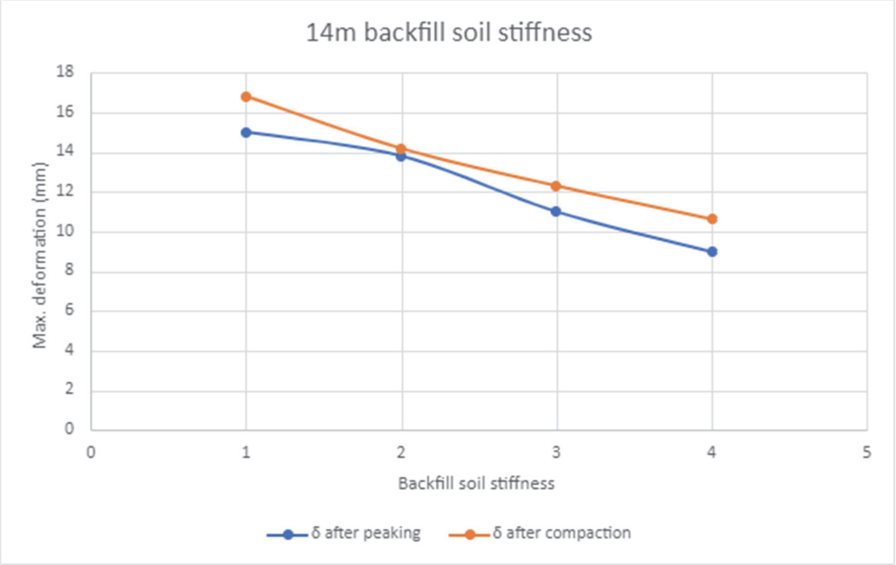
4.5.4 Effect of the Backfill Soil Stiffness

The backfill soil stiffness of the culvert determines its ability to resist deformation under load and can be affected by factors such as soil type, compaction, and moisture content. The main aim is to find the greatest possible stiffness to ensure the material has the highest possible capacity to confine the area. In this case, four soil stiffness values are considered in the numerical models; for a fixed trench geometry and soil cover depth of 1.2 m. The following section explains how different backfill soil stiffnesses (ranging from E_o = 15 MPa to E_o = 90 MPa) affect the crown deformation, bending moment, and thrusts of culverts with small (7m), medium (14m), and large (28m) spans. The following section discusses the variations in crown deformation, bending moments, and thrusts at the crown for three different culvert spans for four different backfill stiffnesses.

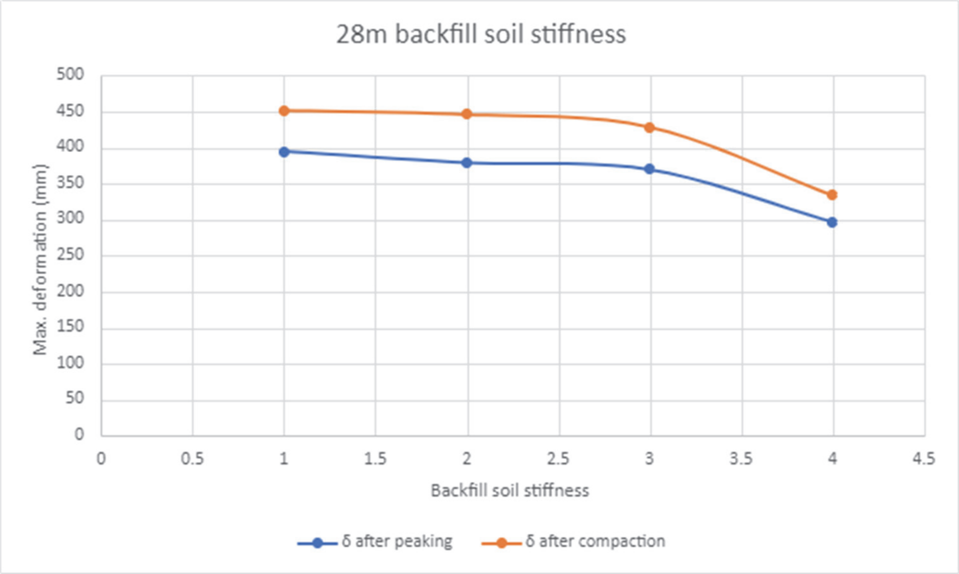
Figure 4.18 compares variations in crown deformation after peaking and compaction with varying backfill stiffness for three different culvert spans. It can be seen that for all three spans of culvert, the crown deformation gradually decreases as the stiffness changes from loose to very dense sand (as the stiffness increases from E_o = 15 MPa to E_o = 90 MPa). The deformations observed in the culvert with loose soil were found to be greater than those observed in the culvert with dense soil. Figures 4.19 and 4.20 compare the variations in bending moment and thrust at three different locations (crown, haunch, and footing) for three different culvert spans. The bending moment and thrusts for all three culverts have the same pattern regardless of their span length. As the stiffness of the backfill soil increased, the magnitude of the bending moment at the crown and haunch areas gradually decreased with a constant magnitude of the bending moment at the footing. This is due to the relative stiffness between the soil and structure. The bending moments experienced by the culvert with loose soil were determined to be 50% higher compared to the culvert with dense soil.



a) Crown deformation after peaking and compaction v/s backfill soil stiffness for 7m span culvert.

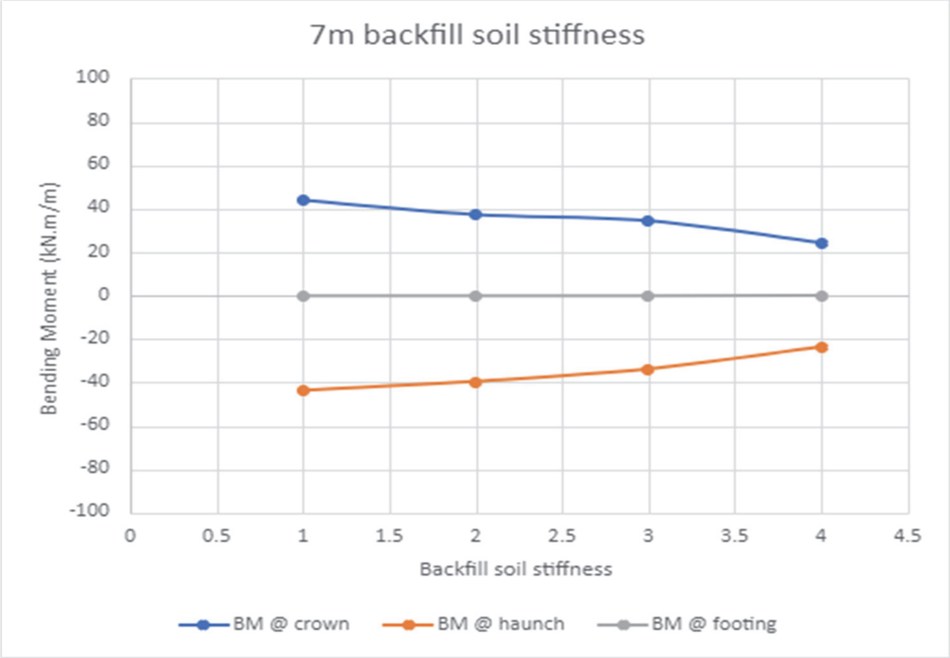


b) Crown deformation after peaking and compaction v/s backfill soil stiffness for 14 m span culvert.

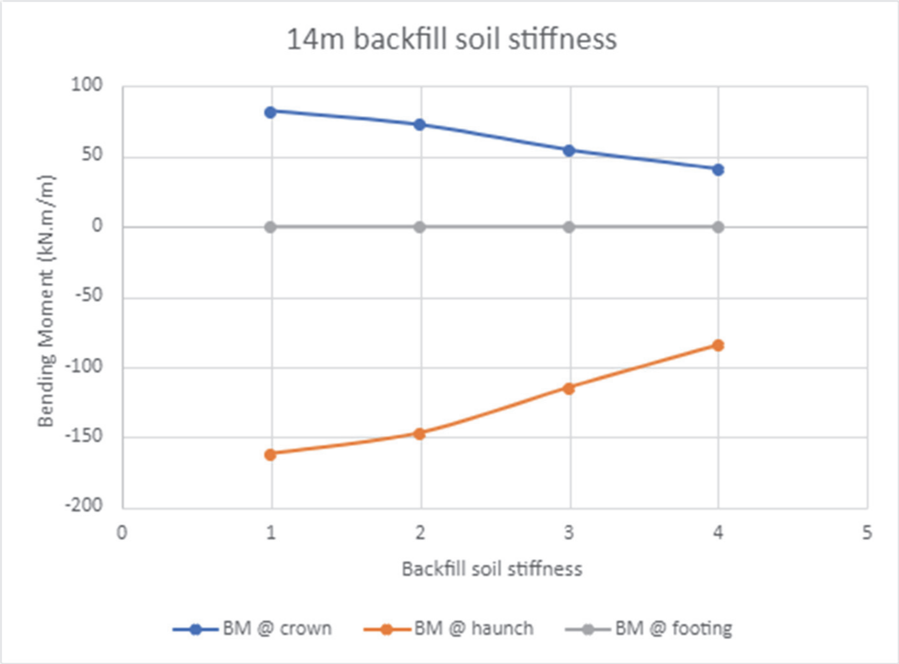


c) Crown deformation after peaking and compaction v/s backfill soil stiffness for 28 m span culvert.

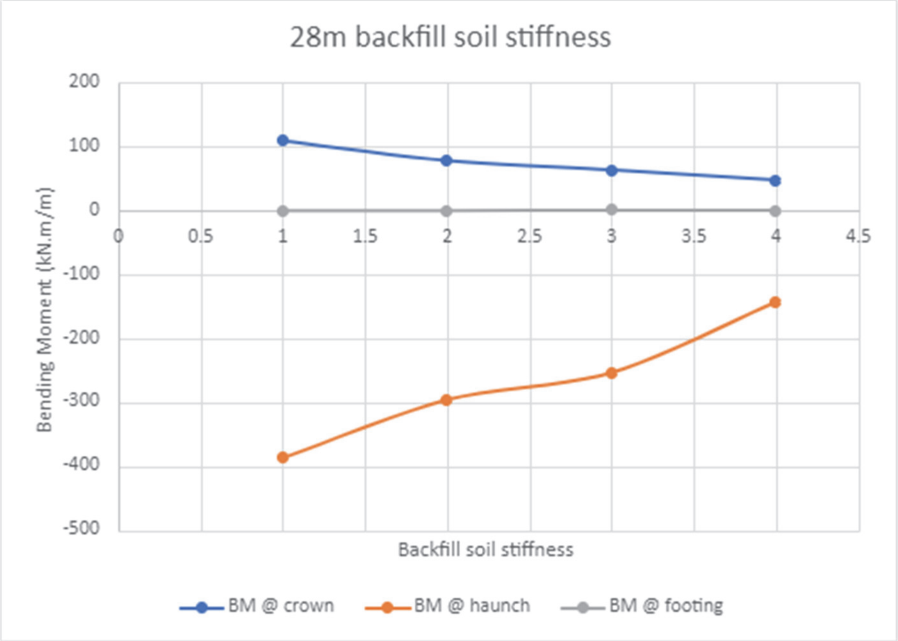
Figure 4.18. Effect of backfill soil stiffness on the crown deformation (after peaking and compaction) for different spans of culvert.



a) Bending Moment v/s backfill soil stiffness for 7m span culvert.

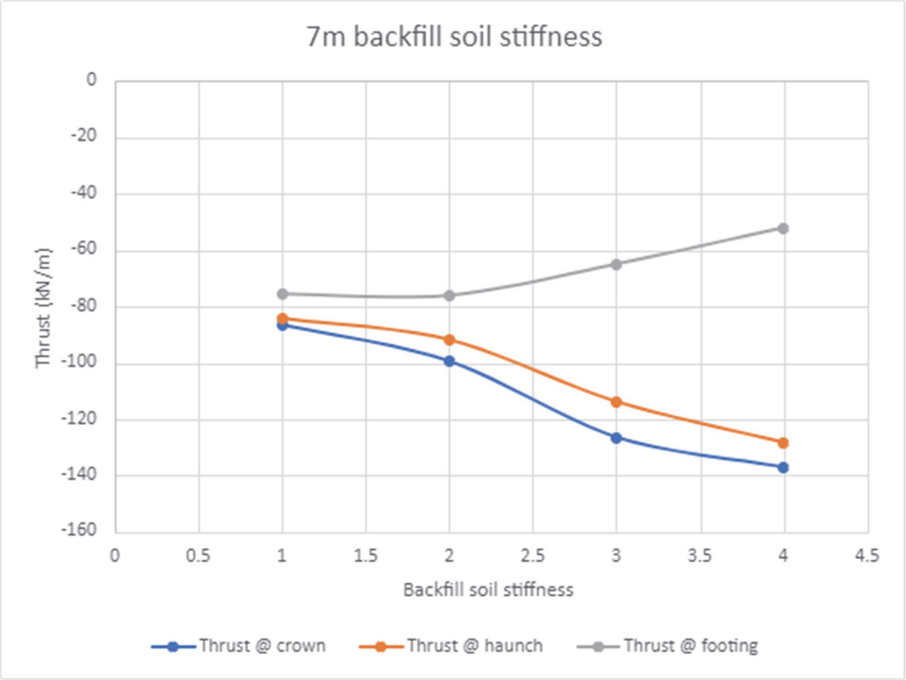


b) Bending Moment v/s backfill soil stiffness for 14 m span culvert.

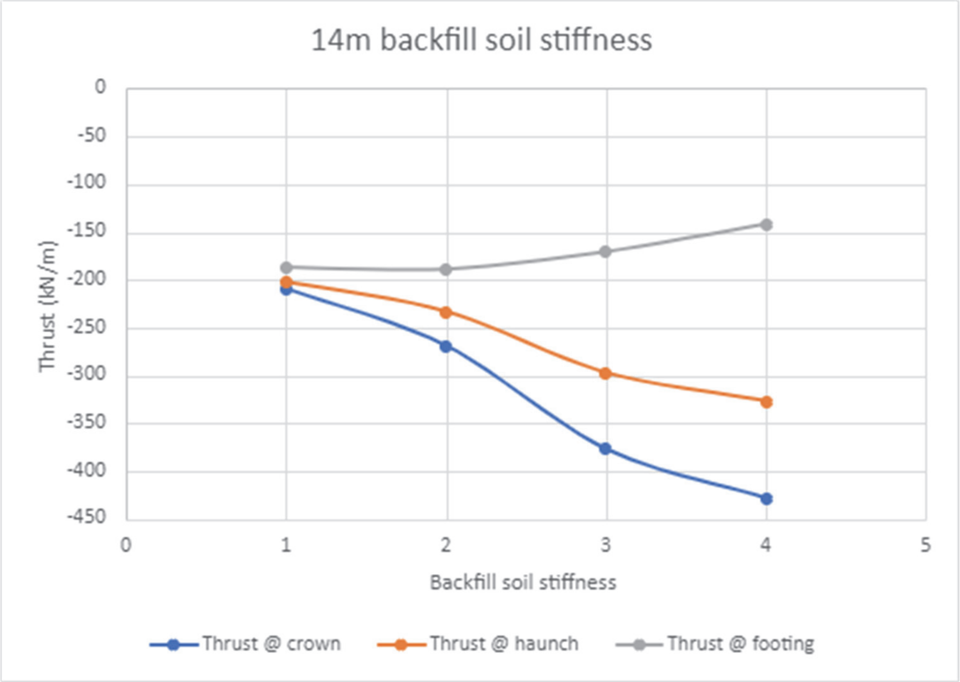


c) Bending Moment v/s backfill soil stiffness for 28 m span culvert.

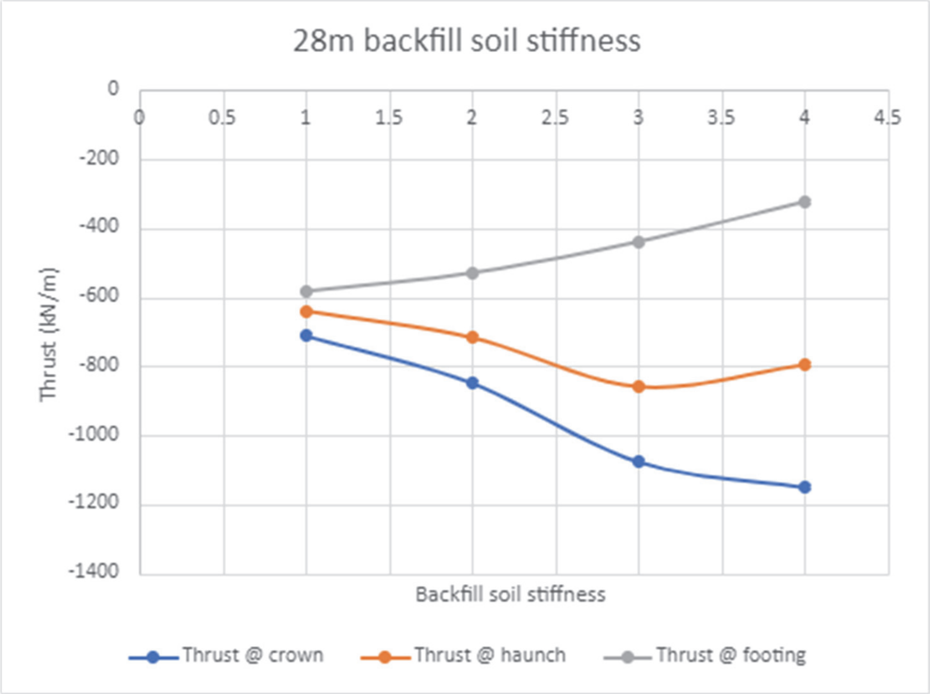
Figure 4.19. Effect of backfill soil stiffness on the bending moment for different spans of culvert.



a) Thrust v/s backfill soil stiffness for 7m span culvert.



b) Thrust v/s backfill soil stiffness for 14 m span culvert.



c) Thrust v/s backfill soil stiffness for 14 m span culvert.

Figure 4.20. Effect of backfill soil stiffness on the thrust for different spans of culvert.

4.6 Conclusion

This chapter presented findings based on parametric studies conducted on three different corrugated box culverts; culvert with small span (7 m), culvert with medium span (14 m), and culvert with large span (28 m). The mechanical response of the box culvert was calculated using two-dimensional analysis. The following conclusions are made:

1) In the finite element analysis, a parametric study was used to investigate several factors that may affect the box culvert design results. It was found that factors such as the soil cover depth and the backfill stiffness significantly affect the results and should be carefully investigated. In contrast, the trench width and the trench side slope of the excavation were found to have only a negligible effect on the results.

2) The trench geometry, the trench width and the trench side slope were found to have no impact on the behaviour of the culvert as the soil-structure behaviour is mainly affected by the backfill soil and the topsoil cover. A minimum trench width of 0.5 times the length of the span and a minimum side slope of 1V:1.5H are considered for constructability and safety.
3) The soil cover depth has a significant effect on the performance of the culvert during backfilling. As the cover depth increases, the total bending moment reduces; at greater soil cover depth, the force applied can spread more of the soil, hence generating lower structural resultants and deflections.
4) Varying the stiffness of the backfill soil was found to affect the performance of corrugated box culverts during backfilling. Increasing the stiffness of the backfill soil significantly increased the earth's pressure. The use of very dense sand is generally preferred in the backfill material.

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS

The performance and behaviour of Corrugated Box Culverts (CBCs) were examined using 2D finite element (FE) modelling. Firstly, a two-dimensional FE model was developed using the Hardening model theory. The 2D model was then validated using full-scale field tests on box culvert conducted by Bayoglu Flener at Lidkoping, Sweden. Secondly, a parametric study was carried out for corrugated box culverts to determine the performance and behaviour of various geometric and material parameters.

5.1 Development of a Two-Dimensional Finite Element Model for Corrugated Box Culverts

In Chapter 3, a 2D FE model was developed to study the mechanical response of Corrugated Box Culverts. The output from the model compared reasonably well with the measured field data. The HSs material model accurately captured the field measurement of the culvert during backfilling. Hence, the HS soil model provides a more rational and realistic model for assessing the soil-structure behaviour and the associated mechanical response parameters. The observed performance of the developed 2D finite element model is deemed sufficient for proceeding with a parametric study in the following chapters.

5.2. Parametric Study for Corrugated Box Culverts

In Chapter 4, several models were developed using the methodology outlined in Chapter 3 to conduct a parametric study on Corrugated Box Culverts. Study parameters included the trench width, trench side slope, soil cover depth, and the backfill soil stiffness. Overall, the corrugated box culvert is most sensitive to the soil cover depth and the backfill soil stiffness. The trench geometry had the smallest influence on the box culvert. The trench geometry, the trench width and the trench side slope were found to have no impact on the behaviour of the culvert as the soil-structure behaviour is mainly affected by the backfill soil and the topsoil cover. A minimum trench width of 0.5 times the length of the span and a minimum side slope of 1V:1.5H are considered for constructability and safety. The soil cover depth has a significant effect on the performance of the culvert during backfilling. As the cover depth increases, the total bending moment reduces; at greater soil cover depth, the force applied can spread more of the soil, hence generating lower structural resultants and deflections. Varying the stiffness of the backfill soil was found to affect the performance of corrugated box culverts during backfilling. Increasing the stiffness of the backfill soil significantly increased the earth's pressure. The use of very dense sand is generally preferred in the backfill material.

5.3 Recommendations

1. Conducting further numerical research to investigate the impacts of stiffeners on the performance and behaviour of Corrugated Box Culverts.
2. By conducting dynamic analysis, the impacts of truck loads on the mechanical response of the Corrugated Box Culvert.
3. Further research should be conducted to evaluate the effects of corrosion on the performance of the Corrugated Box Culvert.

References

1) Aghniaey, N., & Rodgers, N. Sustainability in Design, Construction and Rehabilitation of Culverts. *GEN*, *125*, 1.
2) Amir Ablahad, M., & Rasslan, N. (2023). Harmonised traffic load model between Eurocode 1-part 2 (EN 1991-2) and TRV specifications: A pilot study on reinforced concrete portal frame bridges.
3) Blanc, J. (2013). An analysis of the impact of trash screen design on debris related blockage at culvert inlets (Doctoral dissertation, Heriot-Watt University).
4) Byrne J. H. 1987. Analysis of a Corrugated Steel Box-type Culvert. Master of Science, Ohio University.
5) CHBDC–Canadian Standards Association. (2018). Canadian Highway Bridge Design Code (CHBDC). A National Standard of Canada, CAN/CSA Standard S6-06, CSA International, Rexdale, Ontario.
6) Chu, I., Woo, S. K., Woo, S. I., Kim, J., & Lee, K. (2022). Analysis of Vertical Earth Pressure Acting on Box Culverts through Centrifuge Model Test. Applied Sciences, 12(1), 81.
7) Choi, D., Kim, G. and Byrne, P. 2004. Evaluation of Moment Equation in the 2000 Canadian Highway Bridge Design Code for Soil-Metail Arch Structures. Canadian Journal of Civil Engineering, Vol. 31, No. 2: 281-291.
8) Conesa-García, C., & García-Lorenzo, R. (2013). Evaluating the effectiveness of road-crossing drainage culverts in ephemeral streams. Hydrological Processes, *27*(12), 1781-1796.
9) Damage-Resistant, F. (2018). Materials Requirements. Technical Bulletin, 50.

10) Duncan, J. M., Seed, R. B., & Drawsky, R. H. (1985). Design of corrugated metal box culverts (No. 1008).

11) Embaby, K., El Naggar, M. H., & El Sharnouby, M. (2022). Performance of large span arched

12) soil–steel structures under soil loading. Thin-Walled Structures, 172, 108884.

13) Ezzeldin, I., & El Naggar, H. (2021). Three-dimensional finite element modeling of corrugated metal pipes. Transportation Geotechnics, 27, 100467.

14) Flener, E.B. 2010. Testing the Response of Box-Type Soil-Steel Structures under Static Service Loads. Journal of Bridge Engineering, Vol. 15, No.1: 90-97.

15) Frankiewicz, P., Radecki-Pawlik, A., Wałęga, A., Łapińska, M., & Wojtal-Frankiewicz, A. (2021). Small hydraulic structures, big environmental problems: is it possible to mitigate the negative impacts of culverts on stream biota. Environmental Reviews, 29(4), 510-528.

16) Fu, W., Fu, X., He, Y., & Li, B. (2023). Field test of a medium-size double-span box-type corrugated steel bridge. In Advances in Civil Function Structure and Industrial Architecture (pp. 396-411). CRC Press.

17) Girges Y., Abdel-Sayed G. 1995. Three-Dimensional Analysis of Soil-Steel Bridges, Canadian Journal of Civil Engineering, Vol. 22, No.6: 1155–1163.

18) Hakro, M. R., Kumar, A., Ali, M., Habib, A. F., de Azevedo, A. R., Fediuk, R., ... & Awad, Y. A. (2022). Numerical analysis of shallow foundations with varying loading and soil conditions. Buildings, 12(5), 693.

19) Jeong, Y., Kim, W., Lee, I., & Lee, J. (2018). Bridge inspection practices and bridge management programs in China, Japan, Korea, and US. Journal of Structural Integrity and Maintenance, 3(2), 126-135.

20) Karimpour, S., & Gohari, S. (2020). An experimental study on the effects of debris accumulation at the culvert inlet on downstream scour. Journal of Rehabilitation in Civil Engineering, 8(2), 184-199.

21) Kolerski, T., & Wielgat, P. (2014). Velocity field characteristics at the inlet to a pipe culvert. Archives of Hydro-Engineering and Environmental Mechanics, 61, 127-140.

22) Lougheed, A.C. 2008. Limit States Testing of a Buried Deep Corrugated Large-Span Box Culvert. MSc Thesis, Department of Civil Engineering, Queen's University.

23) Machelski, C. and Antoniszyn, G. 2005. Load Rate of the Circumferential Sector of Soil- Steel Bridge Structures. Archives of Civil and Mechanical Engineering. Vol. V, No. 4: 85-102.

24) Manko, Z. and Beben, D. 2005. Research on Steel Shell of a Road Bridge Made of Corrugated Plates during Backfilling. Journal of Bridge Engineering, ASCE, Vol. 10, No. 5: 184-195.

25) McCavour, T., Byrne, P. and Morrison, T. 1998. Long-Span Reinforced Steel Box Culverts. Transportation Research Report No. 1624, Transportation Research Board, Washington, D.C.: 184-195.

26) Mohammed, H., Kennedy, J. and Smith, P. 2002. Improving the Response of Soil-Metal Structures during Construction. Journal of Bridge Engineering, ASCE, Vol. 7, No. 1: 6-13.

27) Moore, I.D. and Taleb, B.1999. Metal Culvert Response to Earth Loading Performance of Three-dimensional Analysis. Transportation Research Report No. 1656, Transportation Research Board, Washington, D.C.: 37-44.

28) Moore, I.D. and Brachman, R.W. 1994. Three-Dimensional Analysis of Flexible Circular Culverts. Journal of Geotechnical Engineering Vol. 120, No. 10: 1829-1844.

29) Morrison, T.D. 2005. Innovative Low Cover Bridges Utilizing Deep-Corrugated Steel Plates with Encased Concrete Composite Ribs. Paper for Innovations in Bridge Engineering, Annual Conference of Transportation Association of Canada, Calgary, Alberta: 1-27.

30) Rossini, M., Matta, F., Nolan, S., Potter, W., & Nanni, A. (2020). AASHTO design specifications for GFRP-RC bridges. In Proceedings of Italian Concrete Days 2018 (pp. 432-444). Springer International Publishing.

31) Sargand, S. M., Hazen, G. A., Masada, T., & Hurd, J. O. (2018). Long-term field study of a deep-corrugated metal box type culvert. Canadian geotechnical journal, 31(2), 175-180.

32) Tawfiq, S. (2012). Optimization of Culvert Dimensions and Reliability. Optimization, 1, 1-2012.

33) Taylor, J. D., & Singleton, R. D. (2014). The evolution of flow devices used to reduce flooding by beavers: A review. Wildlife Society Bulletin, 38(1), 127-133.

34) Waqas, H. A., Waseem, M., Riaz, A., Ilyas, M., Naveed, M., & Seitz, H. (2023). Influence of Haunch Geometry and Additional Steel Reinforcement on Load Carrying Capacity of Reinforced Concrete Box Culvert. Materials, 16(4), 1409.

35) Wysokowski, A. (2022). Full scale tests of various buried flexible structures under failure load. Scientific Reports, 12(1), 1328.

36) Byrne J. H. 1987. Analysis of a Corrugated Steel Box-type Culvert. Master of Science, Ohio University.

37) Choi, D., Kim, G. and Byrne, P. 2004. Evaluation of Moment Equation in the 2000 Canadian Highway Bridge Design Code for Soil-Metail Arch Structures. Canadian Journal of Civil Engineering, Vol. 31, No. 2: 281-291.

38) Flener, E.B. 2010. Testing the Response of Box-Type Soil-Steel Structures under Static Service Loads. Journal of Bridge Engineering, Vol. 15, No.1: 90-97.

39) Kim, K., and Chai, H.Y. 2005. Design Loading on Deeply Buried Box Culverts. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, Vol. 131, No. 1: 20-27.

40) Kunecki, B. 2006. Full Scale Tests of Corrugated Steel Culvert and FEM Analysis with Various Static Systems. Studia Geotechnicaet Mechanica, Vol. XXVIII, No. 2-4: 39-53.

41) Lougheed, A.C. 2008. Limit States Testing of a Buried Deep Corrugated Large-Span Box Culvert. MSc Thesis, Department of Civil Engineering, Queen’s University.

42) Manko, Z. and Beben, D. 2005. Research on Steel Shell of a Road Bridge Made of Corrugated Plates during Backfilling. Journal of Bridge Engineering, ASCE, Vol. 10, No. 5: 184-195.

43) McCavour, T., Byrne, P. and Morrison, T. 1998. Long-Span Reinforced Steel Box Culverts. Transportation Research Report No. 1624, Transportation Research Board, Washington, D.C.: 184-195.

44) Moore, I.D. and Taleb, B.1999. Metal Culvert Response to Earth Loading Performance of Three-dimensional Analysis. Transportation Research Report No. 1656, Transportation Research Board, Washington, D.C.: 37-44.

45) Moore, I.D. and Brachman, R.W. 1994. Three-Dimensional Analysis of Flexible Circular Culverts. Journal of Geotechnical Engineering Vol. 120, No. 10: 1829-1844.

46) Morrison, T.D. 2005. Innovative Low Cover Bridges Utilizing Deep-Corrugated Steel Plates with Encased Concrete Composite Ribs. Paper for Innovations in Bridge Engineering, Annual Conference of Transportation Association of Canada, Calgary, Alberta: 1-27.

47) PLAXIS 2D, V2021, Reference Manual

48) PLAXIS 2D, V2021, Material Model Manual

49) Webb, M. C., Sussmann, J.A., and Selig, E.T. 1998. Large Span Culvert Field Test Results. Geotechnical Report No. NCH 98-456 F, Department of Civil and Environmental Engineering, University of Massachusetts, Amherst, MA.